FINAL REPORT

Title: Impacts of Climate and Management Options on Wildland Fire Fighting in Alaska: Implications for Operational Costs and Complexity under Future Scenarios

JFSP PROJECT ID: 16-1-01-18

SEPTEMBER 2019

Dr. Courtney Schultz
Colorado State University

Dr. Paul Duffy
Neptune, Inc.

Tait Rutherford
Colorado State University

Randi Jandt
University of Alaska, Fairbanks

Dr. Nancy Fresco
University of Alaska, Fairbanks

Contents

List of Tables

List of Figures

List of Abbreviations/Acronyms

AFS: Alaska Fire Service
AFSC: Alaska Fire Science Consortium
AIWFMP: Alaska Interagency Wildland Fire Management Plan
ALFRESCO: Alaska Frame-Based Ecosystem Code
ANCSA: Alaska Native Claims Settlement Act (of 1971)
ANILCA: Alaska National Interest Lands Conservation Act (of 1980)
AWFCG: Alaska Wildland Fire Coordinating Group
BIA: (US) Bureau of Indian Affairs
BLM: (U.S. Department of the Interior) Bureau of Land Management
CCSM4: Community Climate System Model 4 (National Center for Atmospheric Research)
CMIP5: Climate Model Intercomparison Project (5th version)
CRU: Climate Research Unit (University of East Anglia)
CSU: Colorado State University
DOD: (US Department of Defense
DOF: (Alaska Department of Natural Resources) Division of Forestry
DOI: (US) Department of the Interior
EFF: Emergency Firefighter
GCM: General Circulation Model
GFDL-CM3: (National Oceanographic and Atmospheric Association) Geophysical Fluid Dynamics Laboratory Coupled Model 3
GISS-E2-R: (National Aeronautics and Space Association) Goddard Institute for Space Studies modelE2 Russell
IPCC: Intergovernmental Panel on Climate Change

IPSL-CM5A-LR: Institut Pierre-Simon Laplace Couples Model for the 5th IPCC report, Low Resolution
JFSP: Joint Fire Science Program
MRI-CGCM3: Meteorological Research Institute Coupled General Circulation Model 3
RCP: Representative Concentration Pathway
RTL: Reserve Treaty Rights Lands
SNAP: (University of Alaska Fairbanks) Scenarios Network for Alaska and Arctic Planning
USDA: United Stated Department of Agriculture
USFS: U.S. (Department of Agriculture) Forest Service
WUI: Wildland-Urban Interface

Keywords

Alaska, wildland fire, climate change, fire management, public lands management, adaptive governance

Acknowledgements

This research project was made possible through funding by the Joint Fire Science Program, Project 16-1-01-18. We would also like to thank the members of the CSU Public Lands Policy Group, the Alaska Fire Science Consortium, and the individuals who took the time to interview and participate throughout multiple stages of our project.

Abstract

Under projected patterns of climate change, models predict an increase in wildland fire activity in Alaska, which is likely to strain the capacity of the fire governance system under current arrangements. The Alaska wildland fire governance system consists of the actors, networks, and institutions, including policies and laws, that influence wildland fire management. This system is already adjusting to the effects of a changing climate, but future climate change presents significant uncertainties, with possible higher interannual variability for fire extent and severity that may necessitate new approaches to fire management. We investigated the future of fire in Alaska and possible management and other governance responses and challenges though interviews, interactive workshops, and iterative modeling of fire and vegetation dynamics under future climate and management scenarios utilizing the Alaska Frame-Based Ecosystem Code model (ALFRESCO). Cost projections were iteratively explored with fire managers based on current and anticipated management challenges and opportunities. To elaborate, we interviewed fire managers to understand perceptions of challenges and strategies in the governance system, specifically regarding anticipated changes to fire regimes as a result of climate change. We synthesized our interview data to help inform the creation of future fire management alternatives, which we discussed with fire managers in Alaska in workshops to refine management alternatives. We then used these alternatives to inform ALFRESCO to project fire regimes that correspond to different management alternatives. The results of this work suggest that the fire regime of the boreal forest of Alaska is moving towards a new equilibrium with higher average annual area burned and lower interannual variability. In addition, the boreal forest in Alaska is moving towards a state where fire-initiated secondary succession has a cumulative effect over the next several decades resulting in deciduous vegetation becoming dominant. While the timing of these effects varies among the combinations of climate change and management scenarios, none of the three management scenarios considered, which span the realm of plausible actions that could be taken by the fire management community, have an impact that changes the ultimate fate of the boreal forest. This modeling work suggests that at a landscape scale, the impacts of climate on the fire regime in Alaska are far greater than those that are, or could be, effected by fire management. Throughout this process, we worked iteratively with the fire management community, with the primary goal of understanding the implications of future management alternatives for fire regimes and whether changes to current management approaches or governance structures may be desirable. According to interviewees, the advantages of the current system include the strong relationships and communication among agencies, annual interagency meetings sponsored by the Alaska Wildland Fire Coordinating Group to discuss needed changes to fire management, collaborative arrangements among the agencies and local governments and stakeholders, and the agencies' use of research and science to improve management. Our interview data shows that the fire governance system in Alaska is adaptive to change but faces some capacity limitations that may require changes in interagency policy, structure, or management goals. Based on the challenges and suggestions most commonly mentioned by interviewees, we recommend a focus on four key issues to address going forward: (1) budget processes and allocations; (2) staffing strategies to build capacity; (3) prioritization of values for protection and an assessment of legal and capacity challenges in meeting commitments; and (4) considerations of climate change adaptation and mitigation in fire management.

Objectives

Response to Task Statement

This project was proposed in response to a call for interdisciplinary proposals depicting alternative future scenarios of ecosystem change in Alaska. The call for submission stated:

> *These scenarios are intended as a basis for estimating potential shifts in fuels and fire regimes, and for describing potential management implications. The overall goal of this task is to advise managers of likely long-term effects of current practices, suggest alternative approaches where warranted, and to examine adaptation and mitigation strategies.*

It was noted that proposals should engage both scientists and managers, include a science assessment, and complete an integration and interpretation of this information in an operational (management-focused) scenario analysis. Projects needed to address issues of changing fuels and fire regimes and implications for management programs.

In keeping with these requirements, our project's objectives were to assess current fire regime projections, develop future management alternatives, and use these alternatives to simulate projections of future fire regimes and explore their implications for management costs and decision making in Alaska. In brief, our goals were to understand the following:

1. Current priorities for fire management and how these might change in the future;
2. Advantages and challenges associated with the current fire governance system, particularly in regard to adapting to climate change; and
3. Future needs, opportunities, and potential avenues for improving fire management and fire governance in Alaska.

Our detailed objectives, research questions, hypotheses, and approach in brief are listed below. The objectives of the study were not altered in the course of our work. All objectives were met in the manner intended and described, as will be detailed in this report.

Detailed Objectives

<u>Objective 1:</u> Science Assessment—Characterize the Implications of Future Climate for Fire in Alaska

<u>Research Questions</u>

1.1 What are the projected changes in the fire regimes across Alaska out to 2050?

1.2 How do projected fire regimes vary across future (Climate Model Intercomparison Project (5^{th} version) (CMIP5) General Circulation Model (GCM) and Representative Concentration Pathway (RCP) scenarios?

<u>Hypothesis 1:</u> Key metrics (e.g. cumulative area burned and fire size distribution) of future fire regimes will be significantly different than those for the historical data (1950-2013).
<u>Approach:</u> Analyze spatially explicit historical data along with existing Alaska Frame-Based Ecosystem Code (ALFRESCO) model output with guidance from managers to determine the most relevant spatial and temporal resolution of analyses.

Objective 2: Operational Scenario Analysis—Characterize the implications for fire of alternative management scenarios under future climate scenarios

Research Questions

2.1 Based on future climate scenarios, what are potential alternative management scenarios in the future (e.g. increased or decreased suppression, increased used of fuel treatments, zoning to control wildland-urban interface (WUI) development, etc.) for continuing to meet management objectives?

2.2 How do projected fire regimes in the future change in terms of fire extent and severity under different management scenarios?

Hypothesis 2**:** Different management scenarios will result in significant differences in key metrics of fire regimes.

Approach: Develop a website for managers to explore future fire projections and conduct a workshop and interviews with managers in Spring 2017 to determine alternative management scenarios. Characterize in detail 2-3 potential alternative management scenarios that will inform ALFRESCO modeling to reflect implications of the management scenarios for fire.

Objective 3: Science Delivery—Characterize the Implications of Future Fire for Resource Allocation and Ability to Meet Management Objectives

Research Questions

3.1 Which management scenarios may be preferable in the future and why?

3.2 How are fire-related costs and resource needs likely to change into the future, and to what extent would these costs increase for both state and federal agencies, depending on management approach?

3.3 What recommendations would managers have to policy makers about necessary management and policy changes into the future?

3.4 What are likely future impacts to resources and needs for future research?

Hypothesis 3: Investment magnitude and complexity will significantly differ among future management scenarios.

Approach: Conduct interviews in 2017 to understand management concerns about the future, factors that drive current costs, and likely future costs of fire management. In Fall 2017 workshops, utilize updated model projections and cost estimates to explore the financial and other implications of future scenarios of fire under the different management approaches selected. Subsequently deliver findings in coordination with the Alaska Fire Science Consortium to managers, stakeholders, and high-level policy makers.

Deliverables
Deliverables were outlined in the project proposal as shown in Table 1.

Table 1: Project Deliverables

Deliverable Type	Description	Delivery Dates	Outcome
Website	Interactive website hosted at SNAP that allows users to explore and analyze output from ensembles of ALFRESCO output	Spring 2017	Completed as planned
Presentation to Managers	We will present findings at the Fall Fire Review in coordination with the Alaska Wildfire Coordination Group	Fall 2016 & 2017	Completed as planned
Workshops (2)	Workshops (2) 1st: we will host a 2-3 hour workshop at the Spring AFSC meeting; 2nd: Day-long workshops in Anchorage & Fairbanks	Spring 2017 & Spring 2018	Completed as planned
Webinar	Webinar Conducted with the Alaska Fire Science Consortium Spring 2018	Spring 2017	Completed as planned
Non-refereed Publications (2)	Working paper and policy briefing paper for dissemination via university and fire science consortium websites and social media	Spring 2018	Completed as planned
Refereed Publications (2)	1) Characterization of simulated fire regimes in the context of management-relevant spatial and temporal scales, and 2) Quantifying the interactions between climate and management on future fire regimes and implications for fire management.	Submitted by August 2018	One article on governance findings published online; the second article is in review with the journal
Policy Briefings	Policy briefings We will conduct 8-10 policy briefings in Juneau, AK and Washington, DC with policy makers and leads at the land management agencies who could use our information to further policy change, if needed, and plan for the future.	Spring 2018	All briefings were conducted except in Juneau, AK.
Conference Presentations	Findings were presented at the Society of American Foresters' Annual Meeting and at the Association for Fire Ecology's Fire Continuum Conference	Fall 2017, Spring 2018	Additional deliverables, beyond those that were planned

All deliverable targets have been met, with some adjustments to our policy briefings. Originally, we planned to conduct policy briefings in Juneau and Washington, D.C. with policy makers. We were successful at briefing Bureau of Land Management (BLM) and US Forest Service (USFS) leadership, and Alaska Senator Murkowski's staff in Washington, D.C. Our project contacts and partners in Alaska were not interested or available for briefings in Juneau. In lieu of those meetings, we used funding to present project findings at the Society of American Foresters' Annual Convention and at the Association for Fire Ecology's Fire Continuum Conference.

Background

Fire and Climate Change in Alaska

Alaska's boreal forest ecosystem relies on the regular return of wildland fire to maintain ecological integrity (Kasischke et al., 2010). Rising temperatures and drying soils have recently caused an increase in the frequency of fires, average annual area burned, and average length of the fire season (Kasischke & Turetsky, 2006; Kelly et al., 2013). Fire regime models project these increases will continue with future climate change (Young et al., 2017; Pastick et al., 2017). Rapid climatic changes at high northern latitudes have caused the intensification of fire regimes across boreal and tundra ecosystems in Alaska since the 1980s (Duffy et al. 2005, Kasischke and Turetsky 2006, Kasischke et al. 2010, Kelly et al. 2013).

Researchers have used climate models to project future increases in fire activity over at least the next few decades. Temperature is the strongest determinant of fire occurrence in Alaska (Duffy et al. 2005), and future increases in fire frequency will likely occur as climate change causes exceedance of certain temperature thresholds (Young et al. 2017). Warming average temperatures will also likely increase the average dryness of fuels in boreal ecosystems regardless of changes in precipitation, causing a heightened probability of large fire events (Flannigan et al. 2016). Climate projections for Alaska have predicted increases in statewide average annual fire frequency, area burned, and fire season length during the first half of the 21st century (Mann et al. 2012, Rupp et al. 2016).

Higher severity fires will likely cause transitions in vegetation regimes, resulting in loss of ecosystem services to human communities (Chapin et al., 2008; Rupp et al., 2016). Alaska's isolated and diverse communities are vulnerable to the rapid climatic changes occurring in the region because of their reliance on natural resources for subsistence use (Kasischke et al. 2010, Knapp and Trainor 2015). In combination with climate change, high severity and high frequency fires in the boreal forest can cause lasting shifts toward more early-seral vegetation, and some regions may experience relatively permanent transitions between forested and grassland states (Johnstone et al. 2010, Scheffer et al. 2012, Alexander and Mack 2017). Declines in age class diversity of dominant vegetation with increased burning will likely alter the availability of food for subsistence species such as caribou *(Rangifer tarandus)* and moose (*Alces alces;* Jandt et al. 2008, Joly et al. 2012, Mann et al. 2012).

Elevated greenhouse gas emissions caused by greater fire activity present another challenge, as carbon release from melted permafrost may cause a substantial positive feedback to the global atmospheric greenhouse gas effect (Schuur et al. 2008, Mack et al. 2011, Pastick et al. 2017). Thawing permafrost has also contributed to increased subsidence of land in the tundra, creating an additional positive feedback to carbon release (Jones et al.2015).

Fire Management in Alaska

More frequent large fire years, with high numbers of ignitions and area burned, may strain the ability of Alaska's fire management agencies to protect properties, cultural sites, infrastructure, and valued natural resources (Kasischke et al., 2010). Federal and state funding for fire suppression will need to increase to sustain current management approaches if fire activity increases under climate change (Melvin et al., 2017). Projected future increases in fire activity will likely exacerbate the costs of fire management or leave managers in a position where they are no longer able to maintain fire management activities at current levels (Melvin et al. 2017). Climate change projections show that the number of days that support fire intensities that exceed suppression capabilities will become more frequent in the boreal forest, rendering suppression infeasible at times, regardless of the availability of suppression resources (Wotton et al. 2017). At smaller spatial scales creating breaks in the most flammable boreal fuel types can aid suppression and reduce risk to valued resources; consequently, the use of fuel management by both Alaska's land and fire management agencies has grown (Beverly 2017, Melvin et al. 2018). Fuel reduction treatments, however, do not effectively change area burned or reduce the occurrence of higher intensity fires when assessed at large spatial extents (Cary et al. 2017). Existing evaluations of the need for adaptation to climate change in management in Alaska have suggested the need for risk mitigation on private properties, changes to the initial attack prioritization system, and community organization and cross-boundary collaboration for increased fuel management (Chapin et al. 2008, Trainor et al. 2009).

A unique set of fire management organizations and institutions exist to address the complex social and ecological context of fire management in Alaska (Chapin et al. 2008). To manage wildland fire, the land managers, land owners, and stakeholders participate in a fire governance system (Figure 1), consisting of the actors, networks, and institutions—including the rules, laws, regulations, policies, and social norms—that influence how fire is managed. The actors involved in fire management include federal and state land management agencies and Alaska Native Corporations (collectively called "jurisdictional" agencies), three suppression agencies (called "protection" agencies), Alaska's boroughs, municipalities, and other private landowners (Alaska Wildland Fire Coordinating Group, 2016). The protection agencies are the U.S. Department of the Interior Bureau of Land Management (BLM) Alaska Fire Service (AFS), the U.S. Department of Agriculture Forest Service (USFS), and the Alaska Department of Natural Resources Division of Forestry (DOF) (Figure 2). The AFS and the DOF manage fire in several cross-jurisdictional protection units, while the USFS manages fire primarily on USFS lands (AWFCG 2017). Boxes in Figure 1 represent organizations, agencies, and stakeholders involved in wildland fire governance in Alaska (AWFCG 2017). The inner dotted lines enclose the two

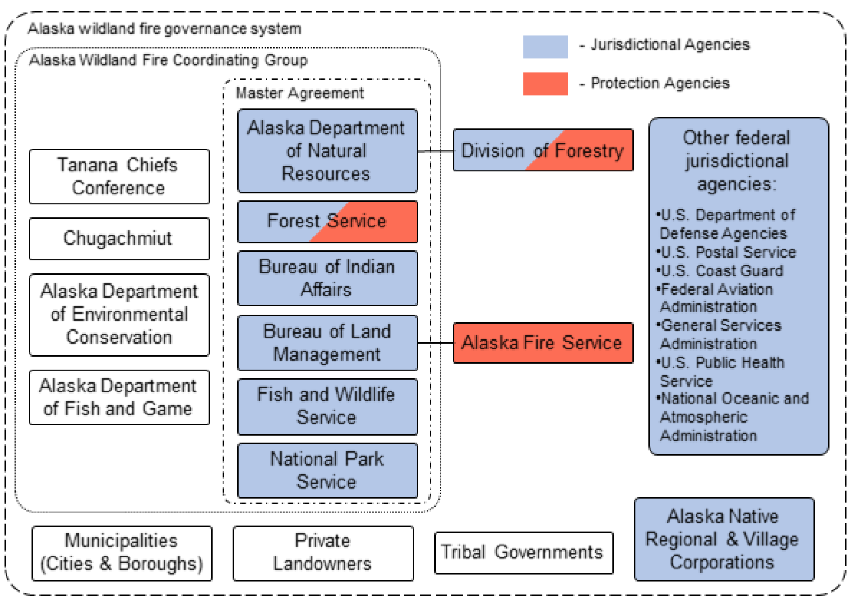

Figure 1: Alaska Wildland Fire Governance System Structure

primary statewide bridging organizations, the Alaska Wildland Fire Coordinating Group (AFWCG) and the Alaska Master Cooperative Wildland Fire Management and Stafford Act Agreement (i.e., "Master Agreement").

This organizational structure shaped current statewide fire governance institutions. In the late 1990s, to simplify translation of land management goals to the protection agencies, the agencies wrote a consolidated Alaska Interagency Wildland Fire Management Plan (AIWFMP) for unified operational direction. In 2010, the agencies also combined prior bilateral interagency contracts into the single Master Agreement (USDOI BIA et al. 2016). The agencies delegate representatives to a committee, the (AWFCG) that coordinates interagency meetings and planning. The AIWFMP outlines an initial attack plan that classifies the entire state into four levels of priority for suppression, called management options, including "critical," "full," "modified," and "limited" (see Table 2).

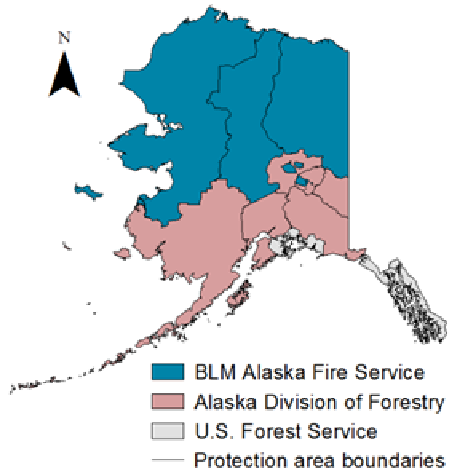

Figure 2: Map of Protection Agency Zones

Table 2: Fire management options (AWFCG 2017)

Management Option	Default initial action	Priority	Values
Critical	Deploy resources to protect sites and suppress fires immediately	Contain fires at the smallest acreage possible	Wildland-urban interface; inhabited property; critical infrastructure; National Historic Landmarks
Full	Deploy resources to protect sites and suppress fires immediately (given resources are not needed to protect areas in critical option)	Contain fires at the smallest acreage possible	Cultural sites; recreation areas; remote structures; high-value natural resources; any other structures or high-value areas not in critical option
Modified	Same as "full" before a predetermined date (usually after peak fire season); same as "limited" thereafter	Same as "full" before a predetermined date (usually after peak fire season); same as "limited" thereafter	Suppression buffer zones adjacent to full or critical; low-priority valued natural resources (e.g., caribou winter habitat)
Limited	Surveillance and small, remote site ("point") protection	Allow fires to burn to the extent possible to support natural ecological processes	Large-scale landscapes with low densities of values

The jurisdictional agencies, with consultation from the protection agencies, prioritize values under these options from “critical” for the highest priority areas for suppression, down to “limited” for areas where the agencies will let fires burn unless they threaten higher priority sites (AWFCG 2017).

The Alaska Native Claims Settlement Act of 1971 (ANCSA) and the Alaska National Interest Lands Conservation Act of 1980 (ANILCA) also shape fire policy. The ANCSA created the Alaska Native Corporations and stipulates that the federal government must sponsor fire suppression on all Alaska Native Corporation and Native allotment land conveyed under the ANCSA (43 USC 1620(e)). The ANILCA mandates that use of federal public lands should have as little impact as possible on subsistence use by rural Alaskans, indicating that the agencies must take into account subsistence hunting, gathering, and timber use values when designating fire management options (16 USC 3112(1)).

While the fire governance system in Alaska has been facing a changing climate and adapting to the demands of more frequent large fire years over the past few decades, future climate change presents major uncertainties regarding fire extent and effects, with possible greater interannual variability and more years with high fire activity compared to the past (Kasischke et al., 2010; Pastick et al., 2017). To continue to protect key values, managers will likely require increased resources and workforce capacity (Melvin et al., 2017). Alaska’s ecological and social context provides a particularly valuable opportunity to explore adaptation to climate change in fire governance (Brunner and Lynch 2010).

The concept of adaptive governance synthesizes knowledge from multiple areas of scholarship to inform understanding of the governance of linked social and ecological systems (social-ecological systems) in the face of uncertainty and rapid change, like that of Alaska (Dietz et al. 2003, Folke et al. 2005). Adaptive governance can be considered an emergent form of environmental governance that supports collective action, the ability of actors to learn and respond to change, and the evaluation of governance strategies over time (Cosens et al. 2018). We use the term governance to mean the processes of decision making to choose and meet goals regarding the use of a public good (Cosens et al. 2018). In adaptive governance systems, scholars have observed that multilevel, networked organizational structures are linked with learning and collective action (Wyborn and Bixler 2013, Morrison et al. 2017). Networks and associated bridging organizations have been observed as critical components of emerging adaptive governance systems (e.g., Olsson et al. 2004, 2008, DeCaro et al. 2017). Allowing for improved fit between governing institutions and ecological scales in a complex network is another critical aspect of adaptive governance (Rijke et al. 2012). Scale-related challenges arise when local governance networks must grapple with climate change and other issues where the scale of the problem and its assessment is distinct from that of management. To create space for local-level governance networks within existing hierarchical structures of regional or national bureaucracies, adaptive governance systems require a degree of reflexivity between local collective action and higher level certainty and stability within the governance system (Craig et al. 2017). Nesting of networks can support collaboration among organizations at local scales within the hierarchical structure, allowing for some flexibility to respond to challenges and needs that occur at different spatial levels (Folke et al. 2007, Wyborn and Bixler 2013). We approached our investigation of the Alaska fire governance system with these concepts in mind.

Materials and Methods

ALFRESCO Modeling

The focus of this project was on the regions where fire is an active agent of ecosystem disturbance in Alaskan ecosystems. Spatially explicit historical fire data (1950-2013) were obtained from the Alaska Interagency Coordination Center (http://afsmaps.blm.gov/imf_firehistory/imf.jsp?site=firehistory), and analogous output from future climate scenarios under the current Fire Management Option approach was obtained from ALFRESCO simulations generated as part of a recently completed NSF-Arctic System Science project (ARC 0612366). We utilized ALFRESCO model outputs to characterize fire regimes under the influence of three different spatially explicit management scenarios and 15 different future climate scenarios in Alaska.

ALFRESCO quantifies interactions among climate, topography, vegetation, post-fire succession, and age-dependent flammability in Alaskan boreal forest and tundra ecosystems (Rupp et al., 2000; Rupp et al., 2006; Rupp et al., 2007). The model simulates the transient states of vegetation at a spatial scale of 1 x 1 km and at annual time steps in response to climate-driven changes in the fire regime (fire frequency, fire severity, and fire size). The fire regime is simulated stochastically and constrained by climate and vegetation type. Ignition is determined randomly and is a function of pixel flammability. The model uses a cellular automaton approach in which an ignited pixel can spread fire to any neighboring pixel (Brubaker et al., 2009). Fire spread depends on the flammability of the adjacent pixels as modified by the presence of firebreaks such as non-vegetated mountain slopes, rivers, and lakes. Post-fire successional pathways are determined by the burn severity in each pixel, which is modeled as a function of fire size and topography (Duffy et al., 2007).

We used ALFRESCO projections of future fire activity by inputting the downscaled climate predictions of the five GCMs found to work best over Alaska (Walsh et al., 2008). These five GCMs were also paired with three distinct representative concentration pathways (RCPs) to produce 15 distinct scenarios of future climate in Alaska. Climate data used in these analyses come from two different sets of data products that cover both the historical (1950-2013) and future periods (2006-2100). Historical (1950–2013) monthly average temperature and total monthly precipitation data come from the CRU TS 3.2 data product (http://www.cru.uea.ac.uk/data), that were downscaled to the 2km spatial resolution (https://www.snap.uaf.edu/tools/data-downloads, retrieval date 3/23/2015) and then resampled to 1km to align with the vegetation map.

The five GCMs (CCSM4, GFDL-CM3, GISS-E2-R, IPSL-CM5A-LR, MRI-CGCM3) were selected based on previous evaluations of performance at high latitudes (Walsh et al 2008). Monthly average temperature and total monthly precipitation data products were obtained from the Coupled Model Intercomparison Project (http://cmip-pcmdi.llnl.gov/cmip5/availability.html). Both the historical data from CRU and the future data from CMIP5 were statistically downscaled using the Parameter-elevation Regression on Independent Slopes Model (PRISM Climate Group, 2012). The result of the statistical downscaling procedure is a spatially explicit 1km resolution map for monthly average temperature and total monthly precipitation. Details about how we down-scaled GCM-predicted climate to the 1 x 1 km scale used in ALFRESCO can be found at http://www.snap.uaf.edu/.

Ultimately, this work generated projections of future fire activity across varying levels of three factors: 1) GCM, 2) RCP, and 3) Management. We implemented a full factorial design in that each level for each of the factors was combined with each level of the other factors. With five GCMs, three RCPs, and three Management scenarios, this yields 45 different treatments (i.e. unique combinations of levels of factors. That is, each of the 15 unique combinations of the different GCMs and RCPs was used in combination with each of three different spatially explicit management maps to simulate fire and vegetation change out to 2099.

The first scenario (Figure 3a) is the current Fire Management Option Map. In this approach, the "modified" protection class is treated as "limited". The protection agencies manage about two-thirds of Alaska under the "limited" management option due to the low density of valued sites and communities across the state, which has allowed for the persistence of natural fire regimes to a high degree in Alaska (Todd and Jewkes 2006). The second scenario (Figure 3b) represents the current Fire Management Option Map with a 10-km increase in the buffer of "full". This results in a 47% increase in the area covered by "full" relative to that of Figure 3a). The final scenario represents complete removal of "full". The scenarios presented in Figure 3b and Figure 3c span the range of what is possible for Fire Management Options. The intent was to construct scenarios that bound the range of possibilities for the future Fire Management Options in Alaska. Taken alone the likelihood of either Figure 3b or Figure 3c being implemented is considered to be quite small as these are sideboards for the range of what is possible with respect to increasing or decreasing the amount of area in "full". The management scenarios in Figure 3a, b, and c, are referred to as TX0, TX1, and TX2 hereafter. TX0 is the continued use of the "status quo" map. TX1 correspond to the current maps with more area in "full". TX2 corresponds to complete removal of "full" (i.e. only areas in "critical" remain).

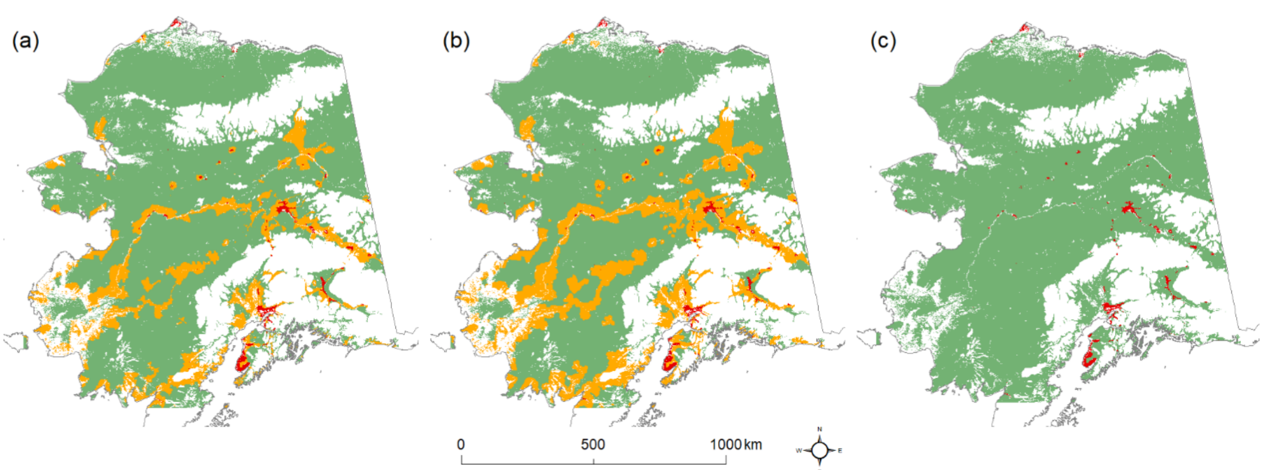

Figure 3: Three different spatially explicit scenarios of fire management considered.
a) TX0, b) TX1, and c) TX2. a) shows the current Fire Management Options (FMO) map. Green corresponds to a combination of "Limited" and "Modified". Tan corresponds to "Full". Red Corresponds to "Critical. The data corresponding to the information in a) can be found at https://fire.ak.blm.gov/content/maps/aicc/Large%20Maps/Alaska_Fire_Management_Options.pdf. b) show the same map as a) with the addition of a 10-km increase in the size of the buffer of full around critical. c) shows the complete removal of full so that only areas in critical remain.

Each of these three different Fire Management Options was used to drive ALFRESCO simulations in conjunction with the 15 different alternative scenarios of climate from 2014-2100. This allows for the characterization of the impacts of both management and climate on key aspects of the fire regime.

In addition, an analysis of the historical costs associated with wildland fire suppression activities in Alaska was performed using historical data from Table 3. Data were derived from the Alaska Interagency Coordination Center's (AICC) Queryable Situation Report (SitQuery) spreadsheet, available for download online and from contacts at the AICC. SitQuery data since 2004 were available, but data were only complete regarding suppression costs since 2011.

Suppression cost data were obtained from two sources (retrieval date: 10/23/18), based on the methods used in Melvin et al. (2017). These two sources were the National Fire and Aviation Management Web Applications website (FAMWEB) ICS-209 form database and the Alaska Interagency Coordination Center's (AICC) Queryable Situation Report (SitQuery) spreadsheet, both downloadable online. The ICS-209 reports provide only data on major fire incidents 2002-2013, and limited data for 2014-2016; some incidents in all reports did not include cost data. The SitQuery spreadsheet included most incidents and costs and acreage for virtually all incidents from 2011-2017, but more limited data on costs relative to the ICS-209 reports from 2004-2010. We triangulated the acreage reported in the SitQuery spreadsheets against acreage reported in AICC annual reports, and found that SitQuery acreage was nearly accurate for 2004-2017. Assuming the SitQuery data for 2011-2017 was the most accurate available data, and because it was the only data set including information on management options and managing agencies, we assembled summary statistics for each year using that data for both acreage and cost, broken out by management option and by managing agency (including private and municipal lands) for the location of ignition, including mean, median, max, min, and standard deviation. For the years 2011-2017, data were compiled on the number of acres burned in each of the three Fire Management Option classes: 1) Critical, 2) Full, and 3) Limited/Modified. For each of these years, a different cost/acre was computed based on the historical cost data.

Table 3: Cost (in dollars) per acre data

Year	Critical	Full	Limited
2011	$2,459	$351	$14
2012	$473	$257	$2
2013	$12,869	$456	$15
2014	$11,160	$76	$295
2015	$198	$89	$14
2016	$6,935	$312	$16

This yields a list of cost per acre for each of the different Fire Management Option classes (Table 3). For each year of an ALFRESCO simulation, a different number of acres burned is observed in the different Fire Management Option classes. In order to compute the estimated cost for a given year of fire activity simulated by ALFRESCO, a value is randomly selected from each of the lists of costs generated from the historical data for the "critical", "full" and "limited/modified" options and multiplied by the simulated area burned in each class respectively. This allows us to project the future costs for the different future projections of climate and management activity. These costs are made using the average of cost data from 2011-2017 and no attempt is made to adjust for inflation. The primary utility of this cost analysis is a relative comparison of the different scenarios considered. This simple approach is not appropriate for an absolute estimate of future costs since that type of analysis requires complexity (e.g. models for inflation, projections for fuel costs, etc.) that is beyond the scope of this project.

Presentation of ALFRESCO outputs

At the AWFCG and Alaska Fire Science Consortium's (AFSC) Fall Fire Review in 2016, members of our team introduced the project, presented initial data on future climate projections and implications for fire, and solicited input from managers at the review on the most relevant spatial and temporal scales of analyses for subsequent model outputs. In a one-day Spring 2017 workshop, conducted in Fairbanks and again in Anchorage, we presented ALFRESCO simulation outputs to managers and explored management scenarios. In this workshop, interim results using simulated output from the increased "full" buffer scenario (Figure 3b) were presented via an interactive website. The website allows managers to explore fire projections at different scales. We developed an interactive website, https://www.snap.uaf.edu/tools/wildfire-management-projections/ (Figure 4 and Figure 5) that allowed fire managers to explore future fire projections under different climate scenarios at various temporal and spatial scales. The site offered a wide range of variables and outputs, so that users could example possible future scenarios for changes in fire, vegetation, stand age, and cover area.

Interviews

Our interviews were grounded in a pragmatic, case-study methodology focused on the Alaska fire management community; our goals were grounded in normative ideals but rather practically informing the future of Alaska fire management in alignment with the community's own goals (Yin 2016). For the interviews used in this study, we recruited participants from AFSC general contact lists and the 2017 Interagency Spring Fire Operations Meeting attendee lists. We began by contacting individuals who our team believed could inform our research objectives, and we conducted additional interviews based on interviewee recommendations until we reached information saturation. We strove to obtain a diverse a set of perspectives and information. Data collection began with an online pilot questionnaire targeted to individuals who had participated in a February 2017, AFSC-sponsored webinar to introduce our project and the beta-version of our fire regime projections website; the questionnaire consisted of seven open-ended questions about current challenges in fire management and the usefulness of our fire regime projections website (see Appendix D). We received 20 responses to the questionnaire, and we used this information to develop and improve the website and to help structure our interview protocol.

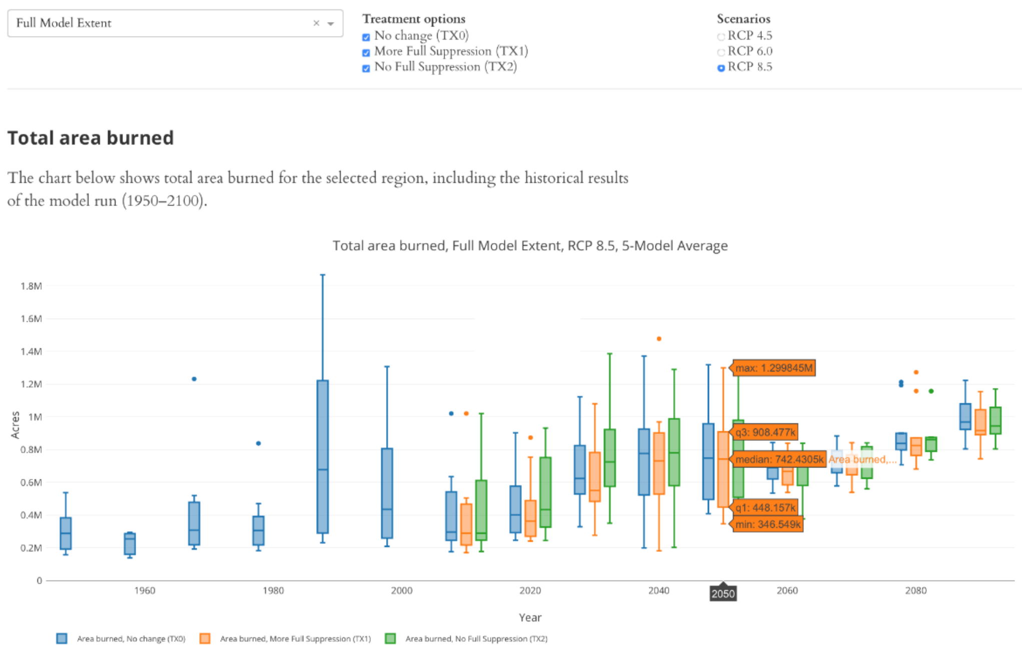

Figure 4: Screenshot of ALFRESCO fire/vegetation simulation website

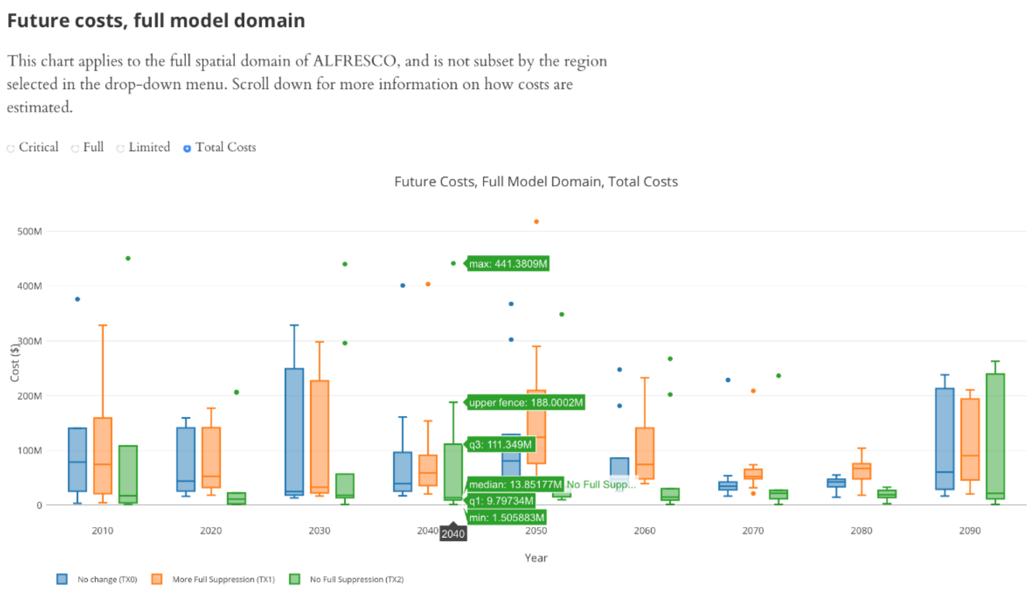

Figure 5: Example of graphical outputs from ALFRESCO website

We prioritized our recruiting of participants from the AFSC lists based on knowledge provided by our collaborators at the AFSC, who were familiar with managers who would be able to provide diverse and informative perspectives. As part of our prioritization, we recruited individuals from as diverse a set of organizations and set of roles and responsibilities as possible within the overarching criterion that they participate in decision making regarding fire management in Alaska. Although we were able to interview individuals from nearly all organizations represented on the AFSC lists, some organizations had greater representation than others because of their higher volumes of fire management staff.

Interviews were confidential and conducted in accordance with requirements and approval from Colorado State University's Institutional Review Board. Starting in March, 2017, we conducted 41 interviews with individuals from the following organizations:

- Alaska Department of Fish & Game (ADF&G)
- Alaska Department of Natural Resources, Division of Forestry (DOF)
- Alaska Native consortia
- Borough emergency services departments
- U.S. Department of Agriculture (USDA), Forest Service (USFS)
- USDA, USFS, State & Private Forestry
- U.S. Department of Defense military bases, fire operations
- U.S. Department of the Interior (DOI), Bureau of Indian Affairs (BIA)
- DOI, Bureau of Land Management (BLM)
- DOI, BLM, Alaska Fire Service (AFS)
- DOI, Fish & Wildlife Service (FWS)
- DOI, National Park Service (NPS)

We conducted and recorded semi-structured, hour-long interviews. We conducted our interviews using an interview protocol (see Appendix D) that consisted of a set of open-ended questions that allowed interviews to flow conversationally and participants to fully articulate ideas from their own perspectives (Yin 2016). Our interview protocol asked about four major topics: (1) current priorities and challenges in fire management; (2) potential future fire management strategies and approaches; (3) needed policy or planning changes to address challenges; and (4) general science needs and feedback regarding our fire and climate model projections.

We recorded and transcribed interviews, then systematically analyzed them using coding software that allows us to assign codes (i.e. labels) to excerpts of text and view all excerpts under each code and in context. Our data analysis process was a thematic analysis, which is a method for identifying, interpreting, and reporting patterns in qualitative data (Braun and Clarke 2006). We began by coding each interview using the online software Dedoose to organize our data according to themes, or common patterns or ideas related to our research questions (Braun and Clarke 2006). We then created memos according to codes (e.g. "management priorities" or "capacity challenges") and associated excerpts. This process allowed us to collate and analyze the large amount of interview data to understand the fire governance system and reflect on what interviewees told us. Once we had fully organized our data excerpts, we referenced these themes and conducted additional coding using potential explanatory concepts in the public policy and environmental governance literatures. Detail on our coding strategy is available in Rutherford and Schultz (2019), our peer-reviewed publication covering our interview findings.

Results and Discussion

Current Fire Management Priorities

Interviewees explained that the agencies set priorities based on state and federal law and external pressure from the public and politicians. Jurisdictional agencies manage fire in accordance with their mandates and missions under a variety of laws. Within these laws, the agencies have some discretion over planning and prioritization, but the laws and agency rules put significant limits on agency priorities. Interviewees emphasized two federal acts that set parameters on prioritizing specific valued resources. The Alaska Native Claims Settlement Act of 1971 (ANCSA) requires that the federal government provide fire suppression to all Native Corporation land and all Native allotments. Under ANCSA, "So long as there are no substantial revenues from such lands they shall continue to receive wildland fire protection services from the United States at no cost" (43 USC 1620(e)). The second federal law affecting fire management is the Alaska National Interest Lands Conservation Act of 1980 (ANILCA), which requires that federal agencies prioritize subsistence use of natural resources by rural Alaskans over non-subsistence use (16 USC 3114). ANILCA also states that public lands use, consistent with existing land management principles, including fire management, should have as little impact on rural Alaskans dependent on subsistence uses as possible (16 USC 3112(1)).

Interviewees mentioned a wide array of values that influence fire management priorities (Table 4). We have organized these values into three categories. The first category of values is reliant on protection from wildland fire, provided by a combination of suppression tactics and the use of fuel breaks and preparedness measures. Virtually all the actors within the governance system agree that protection of human life is the primary priority in fire management; the agencies value firefighter safety and the protection of communities and primary residences above all else. Interviewees consistently said that remote cabins or undeveloped Native allotments will sometimes receive lower priority than other property during periods of high fire activity because remote sites draw heavily on response resources relative to road-accessible areas. The agencies may suppress fires for various other reasons, including preservation of cultural sites, protection of tourist sites, or prevention of smoke pollution. ANCSA Corporations may protect swaths of forest as greenhouse gas pollution offset credits or as timber for biomass. A few interviewees mentioned the potential for placing value on the protection of permafrost for carbon sequestration. As with the protection of carbon offset credits, interviewees expressed concern that protecting permafrost areas would entail a suppression capacity that currently does not exist.

Table 4: Interests and values that drive Alaska fire management

Relationship to fire	Values
Values that require protection from fire	• Cultural and paleontological sites • Human life • Permafrost of timber for carbon sequestration • Property • Reduction of smoke pollution for health • Subsistence hunting opportunities (e.g. caribou winter range) • Timber as carbon emission offset credits • Timber for biomass or other commercial purposes • Tourist sites and viewshed
Values that require fire	• Natural ecological processes • Subsistence hunting opportunities (e.g. moose browse) • Wildlife habitat enhancement
General fire management priorities	• Efficient with taxpayer money • Employment opportunities in fire management

While maintenance of life, property, cultural sites, and tourist sites requires suppression, the agencies otherwise allow natural fire ignitions to burn. As most interviewees agree, Alaska offers a unique opportunity to allow natural fires to burn for ecological benefit due to the low population density relative to the conterminous United States. While climate change has increased fire activity, the agencies still try to allow fire on the landscape as often as they can. Two agencies specifically manage for enhancement of wildlife habitat. Interviewees mentioned that the U.S. Fish and Wildlife Service (FWS) and Alaska Department of Fish & Game (ADF&G) prefer to see natural fires burn when possible to create a diversity of habitat on the landscape. Where this is not possible, ADF&G would like to see increased use of prescribed fire to enhance wildlife habitat. On the other hand, the ANILCA subsistence mandate has recently prompted the protection of caribou winter browse in old-growth black spruce forest in the Kanuti National Wildlife Refuge to maintain hunting grounds for nearby rural villages due to extensive loss of old-growth stands in that refuge in 2004 and 2005.7 According to a few interviewees, this has created some value conflicts for the wildlife management agencies because it contradicts the natural processes paradigm and inhibits moose habitat enhancement.

Some interests are unrelated to increases or decreases in suppression, including careful use of resources and employment opportunities. Agencies said they try to spend public dollars efficiently; a few interviewees from the protection agencies said suppression operations must identify acceptable amounts of risk to be more efficient with resources. A second interest relatively unrelated to suppression is the desire for fire crew employment opportunities among rural Alaskans, especially Alaska Natives. Interviewees said Alaska Native non-profit consortia try to maintain Type 2 Initial Attack crews or Emergency Firefighter (EFF) crews with Native preference hiring to create local employment opportunities. As part of this, the consortia or the villages will often push for suppression or for more fuels projects to create work for the villages. Prioritizing among values (Table 5) is a critical part of fire management and underlies many of the challenges that the agencies currently face, because they have not had the capacity to satisfy all interests and meet all requirements during recent large fire years. Large fire years may force agencies to balance protection of remote sites against saving resources for anticipated ignitions closer to inhabited areas. The agencies also cannot allow unbridled burning for natural processes; sometimes they must balance allowing a fire to burn on public land against risk of it spreading toward adjacent communities.

Table 5: Current key priorities for Alaska fire management identified by participants.

Management priority	Possible approaches going forward
Risk reduction and protection of communities in the wildland-urban interface	Expansion of "critical" and "full" protection buffers around communities; creation of large-scale breaks in flammable fuels around communities to aid suppression; community preparedness, including defensible space
Ensuring the availability of subsistence values, including moose and caribou habitat	Prescribed fire and fire use to promote early postfire age classes near communities; initial attack suppression to protect known caribou habitat near communities
Protection of remote values, including Native allotments and permitted cabins	Identification of all remote sites in the interagency Known Sites Database; efficient point protection and risk acceptance commensurate with the value of the protected site
Carbon sequestration in carbon sinks, including timber and potentially permafrost	Initial attack suppression to protect identified high-priority ecosystem carbon sinks

Advantages within the current fire governance system

According to interviewees, the effectiveness of the current fire governance system in Alaska lies in the strong relationships among the agencies. While interviewees mentioned several areas in which communication within the governance system could be improved, interviewees explained that the separation of the protection agencies from the jurisdictional agencies forces them to maintain constant lines of interagency communication. Protection agency fire management officers (FMOs) work hard to build good relationships with the jurisdictional agencies and landowners to constantly be aware of how they should respond to a fire in any situation. In general, interviewees said that interagency coordination in Alaska is very healthy. Documents such as the Master Agreement and the Alaska Interagency Wildland Fire Management Plan codify the interagency system by clearly defining agency responsibilities. In addition, interviewees noted that the biannual interagency meetings sponsored by interagency organizations allow the agencies to refine planning and operations.

Outside of the interagency system, interviewees said that the agencies benefit from collaboration with local governments and the public. Prevention officers for Alaska Division of Forestry (DOF) host public education programs on fire preparedness and prevention throughout the state. In addition, local collaborative initiatives coordinate large-scale, cross-jurisdictional fuel breaks, preparedness, and recovery projects. Many interviewees cited the Kenai Peninsula's All Lands/All Hands group, which coordinates planning and resource sharing for fuels projects between federal, state, Alaska Native, and local governments, as an ideal example of collaborative fire management. A few interviewees also said that some of the agencies would like to set up groups like the Kenai All Lands/All Hands group in other areas, but that such collaborative work is often not feasible outside of the more densely populated regions of the state such as the Kenai Peninsula or the Fairbanks area.

Interviewees mentioned a few mechanisms in the current governance system that enable adaptability to change. For example, the biannual interagency meetings allow agencies to continually refine fire management based on current circumstances and values. The agencies also try to use science and research to inform management decisions. In part, this effort to improve operations and communication has resulted from a widespread realization among the agencies that they must anticipate climate change and the need to better understand its effects.

Challenges within the current fire governance system

Interviewees suggested including a broader array of actors in the governance system will improve communication regarding values and limitations. For example, a few interviewees mentioned that the inclusion of Department of Defense (DOD) agencies in the Master Agreement would facilitate billing between the protection agencies and DOD. Interviewees also explained that despite current agency efforts, there is a need for more education and outreach. Interviewees said this would help with communication of values and priorities between the agencies and other groups in the governance system, including ANCSA Corporations, communities, and politicians. At the same time, some agency interviewees suggested that the public and the ANCSA Corporations may have opportunities to involve themselves to a greater extent in fire management to improve preparedness and their understanding of the limits and priorities of the agencies.

Within the governance system, interviewees felt that some groups of agency personnel could become better involved in fire management to improve the system. Some interviewees suggested that the state jurisdictional agencies could consider fire risks when zoning and selling or leasing land. Many interviewees felt that the jurisdictional agency administrators could also be more involved in fire management. The agency administrators manage public lands resources and write the land and resource management plans that inform fire management planning. Involving agency administrators more directly in fire management would improve the communication of landscape goals to the protection agencies so that they could tailor suppression decisions and implement more targeted fuels work. Interviewees felt both that agency administrators need to work to involve themselves in fire management more and that the protection agencies need to reach out more to the agency administrators. An interviewee explained that some agency administrators have begun to attend the annual interagency fire management meetings in order to become more involved in fire management.

Many interviewees also felt that the jurisdictional agency FMOs need to become more involved in the annual review of management option designations in the Alaska Interagency Wildland Fire Management Plan (AIWFMP). Some of the protection agency interviewees believed that significant inconsistencies in the management options map need to be addressed. For example, one interviewee explained that the agencies have not holistically reviewed the original management option designations. A few interviewees from the protection agencies suggested the creation of an interagency, interdisciplinary team that would work exclusively on management option changes. Such a team would review the current management options map in detail, replacing the current annual review system, to fix any inconsistencies across management areas or needed changes based on changes in valued resources.

On the other hand, interviewees from several agencies, including AFS, felt the protection agencies could focus more on fuels work and land management considerations. Several interviewees noted that the protection agencies are relatively specialized in suppression activity. Many of the jurisdictional agencies would like to allow more fire on the landscape, but the protection agencies may not want to accept the risk of allowing natural fires to burn.

Capacity and resources

Interviewees emphasized that challenges in fire suppression arise in particular during large fire years, which pose a threat to multiple types of values, and models indicate they may become more frequent. On the one hand, large fire years strain the capacity of the protecting agencies. The agencies are accustomed to dealing with these events about once per decade, but interviewees expressed concern that if the frequency of large fire years increases under climate change, the agencies will more often not be able to protect the valued resources that they intend to be protecting. On the other hand, even if the agencies were to have unlimited suppression resources, they worry that they might lose the ability to allow fire on the landscape, due to ecosystem transitions and risk to communities as a result of unusually large and severe "megafires."

Most interviewees focused on challenges stemming from limited capacity; interviewees said that insufficient funding has affected operations, fuels projects, and hiring. During large fire years, agencies in Alaska borrow equipment and staff from their counterparts in the conterminous United States, but borrowing will not be available if fire seasons lengthen in both the Lower 48 and in Alaska. The protection agencies also are concerned that changes in shared interagency equipment and staffing policies under nationwide federal agency regulations will reduce operations capacity in Alaska. DOF and Alaska Fire Service (AFS), for example, want to make sure that fuel-efficient air tankers suited to the long-distance flights common in Alaska suppression operations remain available for use. It is also becoming more difficult for the protection agencies to afford EFF crews, due to requirements for increased training and growth in crew size. Interviewees mentioned that many of the agencies would like to implement more fuel breaks to ease potential suppression or enhance habitat, but funding for fuels projects is limited, especially in Alaska, where fuels projects are unusually expensive and unlikely to encounter a natural ignition before regrowth. In remote areas, suppression is often cheaper than implementing a fuel break.

To ease funding challenges, interviewees suggested possible changes in budgeting processes or more pooling of funding sources among agencies. For example, many interviewees explained that fire budgeting for the Department of the Interior (DOI) and the Bureau of Land Management (BLM) uses risk-based statistical models designed for suppression operations in the conterminous United States; those model do not always apply well in Alaska where values to protect are different, the interagency governance structure is different, and suppression operations often focus on protection of sites rather than minimization of acreage burned. Other interviewees suggested consideration of innovative funding structures used by other states, such as purchasing insurance for the state suppression agency or implementing a flat annual tax on property located in the wildland-urban interface (WUI). Interviewees also explained that collaborative governance arrangements may help agencies and communities obtain money from federal grant pools, such as Cohesive Strategy funding, for fuels projects. For example, municipalities and villages with Community Wildfire Protection Plans are more likely to be able to win federal grants. Interagency organizations such as the Kenai Peninsula All Lands/All Hands group have been able to pool money from various sources: while communities in the Kenai Borough can get federal grants, ADF&G can use Federal Aid in Wildlife Restoration (Pittman-Robertson) Act funding for fuels projects as habitat enhancement, the Chugachmiut Alaska Native non-profit organization can use Reserve Treaty Rights Lands (RTRL) program funding from the Bureau of Indian Affairs (BIA), and FWS and DOF can use their own operating budgets.

Limited funding is interrelated with staffing challenges. Interviewees expressed that funding directly affects the ability of agencies to retain staff and hire new staff. Many interviewees mentioned several other issues associated with staffing at multiple levels, including: lack of competitive pay in firefighting jobs relative to similar types of work; workforce demographic shifts toward white-collar careers, resulting in fewer recruits for firefighting jobs; consolidation of jurisdictional agency fire offices and closing of protection agency outstations; lack of experience among fire managers; a need for more flexibility in staffing regulations; limits on the sharing of staff across agencies; and lack of fire-related positions in jurisdictional agencies. With the scarcity of personnel at many levels, interviewees said the agencies lose capacity for suppression operations and fuels projects. To solve staffing issues, interviewees suggested more localized decision making on staffing levels, longer staffing seasons for seasonal employees, and easier processes for interagency hiring and staff sharing for projects.

Future management strategies

To improve on the current situation and address challenges associated with anticipated climate change, interviewees suggested some changes in fire management policy and approaches going forward. Interviewees explained that coalescing interagency policy in a few areas to prevent policy gaps, conflicts, or redundancies could improve the efficiency of the governance system. Interviewees emphasized two primary types of policy incongruence in the governance system, including remote cabin protection policy and the agency certification and permitting processes. Protection policy for remote cabins is not uniform across jurisdictional units. In addition, when the jurisdictional agencies do not have cabin protection policies (e.g. BLM), the protection agencies have their own policy on whether they should protect a remote structure. The protection agency FMOs are often reluctant to allow any structure to burn, but agency policy may dictate that they should not protect certain structures, such as an uninhabited trespass cabin.

The second area of policy incongruence is agency certification and permitting. Overlaps in administrative requirements create significant inefficiencies and delays in projects. For example, when agencies share air resources, they may not recognize each other’s certification and safety inspections, and similar inspections may occur multiple times for a single use of an aircraft. The agencies also do not recognize each other’s personnel training certifications, such as ATV/UTV use training.

Interviewees also discussed two broad ideas for changes in management approaches to address anticipated challenges associated with climate change, including broad changes in management options and increased use of fuels work. These two ideas formed the basis for our future management alternatives with which we will modify our fire regime projections outputs using the ALFRESCO model. We talked with many interviewees about the possibility of broad management option changes in response to either higher risk or limited resources. These interviewees generally explained that the expansion of critical, full, and modified management option designations to avoid risk is much more likely than their reduction to avoid expense. Interviewees also explained that expanding management option buffers around communities to reduce hazard to those communities during increasingly frequent times of high fire danger is much more likely than designating wide swaths of forest under the full or modified management option to protect carbon sinks and avoid the occurrence of unusually large and devastating fires. Many interviewees expressed concern that excessive suppression would lead to fuel buildup and exacerbate future fire severity.

An additional fire management approach interviewees discussed was an increased use of large-scale, cross-jurisdictional fuel breaks to address increased fire activity anticipated with climate change. These would facilitate potential suppression around communities and allow some natural burning relatively closer to communities. While fuels work is prohibitively expensive around many of the more remote sites and communities in Alaska, many interviewees said that the creation of fuel breaks around road-accessible communities and in more densely populated areas would make future suppression operations easier. Many interviewees cited recent successes of large-scale, cross-jurisdictional fuel breaks created by the Kenai All Lands/All Hands group as evidence to support greater funding and collaboration for fuel breaks. A few interviewees also explained the perceived benefits of increasing prescribed fire application in the future to accomplish both fuels reduction and habitat enhancement.

One interviewee suggested that fuels work should be funded through the resource management budgets in the jurisdictional agencies in addition to through the protection agency budgets, because fuels work is currently underfunded through the protection agency budgets. Interviewees explained that while protection agencies possess the expertise to execute fuel treatments, jurisdictional agencies set landscape goals supported by specific fire-related outcomes. Many interviewees cautioned that although changing the agencies' approach toward fuels work in Alaska has potential benefits to many values, it must be balanced with the large expense that it may entail.

Projections of future fire regimes

Our project examined output from a simulation experiment that generated projections of future fire activity across different levels of three factors: 1) GCM, 2) RCP, and 3) management scenario. We implemented a full factorial design so each level for each of the factors was combined with each possible level of the other factors. With five GCMs, three RCPs, and three management scenarios, this yields 45 different treatments (i.e. unique combinations of levels of factors). In general, differences among the five GCMs reflect uncertainty associated with the architecture and design of the inner workings of these models. The differences in model output among GCMs are of interest in terms of accommodating the uncertainty in the future projections associated with GCMs differences. However, it is not a direct focus of this work to characterize why different GCMs correspond to differences in outputs. Given this, in order to simplify the presentation of results here, for each year and response variable of interest, median values across GCMs were used to summarize output. Difference among the outputs as a function of RCP and management scenarios were then considered using the median outputs across the GCMs.

Differences among RCPs reflect potential trajectories that humans could realize in terms of key drivers including population growth, types and amount of energy production, and other important aspects of human development. Differences among these RCPs reflect the extent to which changes in the trajectory of human development could influence the fire regime vicariously through impacts on future climate. While, differences among RCPs do exist with respect to the timing and magnitude of changes in fire activity, vegetation change and costs, results were fairly consistent across RCPs with respect to projections for future fire regime. Consequently, in order to simplify the presentation of these results we present graphical output from the "middle of the road" RCP 6.0. In order to assess the hypotheses of interest, the Kruskal-Wallace test for differences in measures of center corresponding to key fire regime variables were performed. The p-values for these tests are shown in Table 6.

Table 6: P-values for Kruskal-Wallace tests of difference in the measures of center.

	2050	2090
Area burned		
RCP 4.5	0.63	0.86
RCP 6.0	0.73	0.86
RCP 8.5	0.90	0.31
Cost		
RCP 4.5	0.28	0.73
RCP 6.0	0.44	0.34
RCP 8.5	0.16	0.39

Differences among the management scenarios are of the greatest interest here, and we focus our presentation of the results accordingly. Recall that, the management scenarios in Figure 3a, b, and c, are referred to as TX0, TX1, and TX2, respectively. TX0 is the continued use of the "status quo" map. TX1 corresponds to the current map with the exception that about 50% more area in placed in "full". TX2 corresponds to complete removal of "full" (i.e. only areas in "critical" remain).

The first hypothesis was "*Key metrics (e.g. cumulative area burned and fire size distribution) of future fire regimes will be significantly different than those for the historical data (1950-2013)*." One simple metric that integrates key components of the fire regime is area burned. Figure 6 shows boxplots of annual area burned (aggregated by decade) for each of the three management scenarios. That is, each boxplot represents 10 values, one for each year within the respective decade (e.g. 2020 includes 2020-2029). The axis for the area burned information is on the left of the graph. The boxplots show key statistics of interest graphically. The median is the horizontal line in the middle of the box. The colored region of the box extends to the inter-quartile range (IQR) which is the region between the 25th and 75th percentiles. The whiskers extend to the largest data point that is both outside the box but less than the median +/- 1.5*IQR. Anything outside +/- 1.5*IQR is shown as a dot for consideration as an "outlier". In this context, outliers are simply extreme values that are still considered part of the distribution of interest. There is also a horizontal line (~ 112,000 ha) placed on Figure 6 indicating the historical average annual area burned for the period 1950-2013. This is provided for context to show the relative magnitude of the future projections juxtaposed against information from the historical data on area burned.

Figure 6: Boxplots of annual area burned shown for decades in the simulation period

The boxplots show a significant increase in area burned that is projected for the entire simulation period yet most pronounced for the next several decades. All of the 25th percentiles for projected annual area burned are greater than the historical average. There is a relative decrease in the area burned between 2040 and 2060. Another increase in area burned is then observed from 2060 onto 2099.

Another metric that integrates information from key components of the fire regime is interannual variability. This statistic is computed as the variance of the annual area burned for 10-yr rolling windows. This information is presented as lines on Figure 6 with the axis labeled on the right of the graph. When fire seasons are episodic with years experiencing large area burned being followed by years with relatively little area burned, the inter-annual variability will be large. This effect is observed in the 2020 and 2030 decades. When the amount of area burned among years is relatively more consistent, the interannual variability will be lower. This is observed in 2040-2060. The projections suggest a fairly dramatic increase in the inter-annual variability of annual area burned over the next several decades. This increased variability from year to year would likely have implications for planning and budgeting in terms of fire management operations. This increase variability also corresponds to the overall increase in the projected annual area burned. Relative decreases in the inter-annual variability in the 2040s and 2050s correspond to relative decreases in area burned as well. This reflects a more consistent amount of area burned from year to year. Taken as a whole, the projections suggest that after several decades of increasingly variable and large magnitude annual fire events, the future fire regime will stabilize with increased area burned with less interannual variability relative to the present.

The second hypothesis of interest was "*Different management scenarios will result in significant differences in key metrics of fire regimes*." When interpreting potential differences in simulation output, it helps to understand that the alternative management scenarios considered for the simulation experiment (i.e. TX1 and TX2) were intended to be extreme cases of what is possible for future management with neither extreme having a high likelihood of being implemented exactly as depicted here. The p-values in Table 6 correspond to the test of the hypothesis that the annual area burned for each of the three management scenarios is effectively equal. This Kruskal-Wallace test is effectively the non-parametric analog to an ANOVA. These tests were performed for the decades of 2050 and 2090. For each of these decades, if any management scenario had a central tendency of annual area burned that was significantly different from the others, the statistical significance would be indicated by a small p-value (e.g. less than 0.05). The lack of significance (Table 6) suggests that there were no meaningful differences in the annual area burned. Ultimately, the impact of the climate forcing on the fire regime overwhelms the impact of the different management scenarios considered.

The final hypothesis of interest was "*Investment magnitude and complexity will significantly differ among future management scenarios*." It is again useful to consider that the management scenarios were sideboards that constrain what is possible both politically and logistically. Figure 7 shows similar boxplots to those presented for the annual area burned data except here they are applied to the projected costs. One of the more noticeable features is the relatively wide IQR displayed by projections for each management scenario in 2040. Despite this, the medians for the respective scenarios are similar from 2030 to 2040. The expansion of the IQR also corresponds to the absence of "outliers" present in the 2020s and 2030. Effectively, this is indicative of a compression of the distributions of costs. This is driven by the transition of the landscape from one with large pockets of flammable coniferous vegetation to one with smaller patches of coniferous vegetation and more regularly spaced deciduous vegetation.

The lines on Figure 7 show the ratio of coniferous to deciduous vegetation. There is a dramatic transition occurring across the landscape as a consequence of the significant increase in fire activity projected for 2020 and 2030. In the 2040s the last remnant large patches of coniferous vegetation are burning and at the same time the inter-annual variability of the area burned is decreasing. The large outliers of cost in the 2030s do not show up in the 2040s yet there are more values around the upper quartile that result in a larger IQR. By the 2050s the fire regime seems to reach a new equilibrium with significantly less coniferous vegetation on the landscape and a more consistent annual area burned. As the landscape moves towards a new equilibrium, the projected costs associated with fire management stabilize from 2050 through the 2090s.

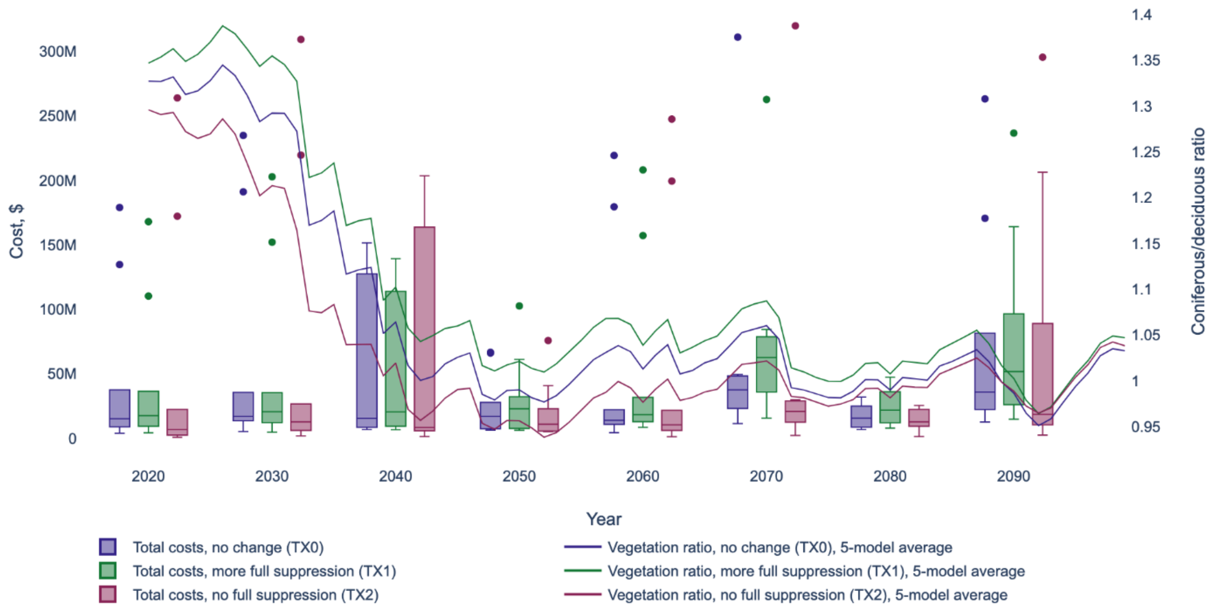

Figure 7: Projections of cost and relative dominance of differentially flammable vegetation types

The general trend among all three management scenarios is a substantial increase in the annual area burned for the next several decades. This increase is consistent across management scenarios. TX1 effectively represents a philosophy of attempting to suppress more fire. As expected, TX1 does result in slightly lower area burned, but, however, there appears to be little meaningful change (with respect to statistical significance) in either area burned or costs in the future at the landscape scale. The impact of the climate signal on the fire regime overwhelms any effects of the TX1 management scenario. One of the concepts behind the TX2 ("no full") scenario was to allow the landscape to burn more in the near term and possibly take advantage of the negative feedback of the establishment of lower flammability deciduous vegetation to decrease the overall flammability of the landscape. The landscape scale negative feedback that was posited with this approach never materializes as the median area burned for the TX2 scenarios is consistently (but not statistically significantly) higher than that of the other two scenarios. Regardless of the management scenario, the inter annual variability and the coniferous to deciduous ratio mover steeply over the 2030s and 2040s. A new steady state is reached around 2050 and the increasing climate forcing results in a slow increase of fire activity in the second half of the simulation period. Ultimately, the ability for any plausible management scenario to mitigate the effects of climate forcing seems limited.

Conclusions

Implications for Management and Policy

Alaska has experienced several extraordinarily large wildfire years in recent decades; our model predicts sustained, higher levels of both annual fire activity and inter-annual variability through about 2040. These projections suggest that there is another decade or two where higher fire activity, increased interannual variability in annual area burned will be experience. The forecast also suggests that the reduction of coniferous vegetation on the landscape will persist. In the second half of the 21st century, because of the transition to a less flammable landscape, our findings suggest the annual extent of fire will decline from its maximum then stabilize, with higher annual burn area and lower inter-annual variability than the historical average. The results are consistent across all GCMs, RCPs, and management scenarios. Our results suggest that the effects of climate greatly outweigh those of possible management actions at the landscape scale.

Increases in fire activity may require greater funding and capacity and a reevaluation of fire management expectations. In recent large fire years, managers have not had enough resources to meet all fire management obligations. If resources continue to decline relative to fire activity, fire managers say they will not always be able to protect remote values, such as cabins, Native allotments, and areas protected for subsistence use or ecological benefit. In addition, as populations grow and the road network expands, firefighting costs will likely increase significantly for the State, which has responsibility for fire management in the more populated regions of Alaska. In light of anticipated capacity limitations, continual communication among members of the fire management community about agency limitations and stakeholder priorities will be critical. To address capacity limitations, study participants recommended:

- Increasing base funding;
- Increasing the duration of appointments for seasonal firefighters;
- Reviewing training requirements to ensure use of available human resources, including the Emergency Firefighter Program; and
- Considering fire risk prior to permitting suburban development or remote structures.

Managers suggest a need to implement more extensive fuel breaks to reduce the risk of fire to communities and maintain the ability to allow fires to burn where possible. Creating fuel breaks near communities is a way to meet the dual challenge of an expanding population and increased fire activity. Fuel treatments augment decision space for managers and increase the safety and success of firefighters on the ground. Communities can consider the model of the Kenai Peninsula, where state and federal agencies, the Kenai Borough, Native organizations, and local communities have successfully collaborated since the early 2000s to implement community education and outreach, forest health projects, and multiple cross-jurisdictional fuel breaks, several of which have helped firefighters to save homes.

Fire managers consistently discussed a need for reevaluation of Native allotment protection policy. Federal law guarantees fire protection for all allotments. Remote allotments can be expensive and dangerous to protect. The State often incurs significant costs fighting fires to protect allotments in areas where they otherwise would not fight fire. Allotments receive default "full" protection under current policy, but managers said some allotment owners would prefer to let fires burn across their land to enhance wildlife habitat. Interviewees offered three potential approaches to addressing allotment protection:

- Revisiting allotment protection levels and strategies in a systematic and deliberative process by engaging key federal agencies;
- Creating venues for direct communication during fire events between allotment owners and fire management agencies, or through organizations such as the Tanana Chiefs Conference and Chugachmiut; and
- Addressing management costs incurred for allotments separately from costs for other types of management.

Fire managers anticipate challenges associated with managing for climate change. Fire increasingly is burning in novel ways and locations, suggesting a need for ongoing research regarding fire effects and close interaction among fire and land managers. Managers also expressed trepidation about protecting Native Corporation land sold as carbon offset credits in the California carbon market, especially during the inventory period when losses are not insured. Protection responsibility for these lands could shift to the State if carbon credits begin to yield revenue.

We have identified four broad policy areas to address going forward based on the issues consistently discussed by interviewees:

1. <u>Budgeting and Funding:</u> Funding already limits the protection agencies' ability to meet all of their protection obligations. Interviewees stated that the tendency for legislatures to prefer to allocate emergency supplemental funding, rather than increase annual budgets, makes it difficult for them to plan and prepare resources effectively. Interviewees noted, however, that Alaska's wide swings in fire activity from year to year make it difficult to avoid either over-allocation or under-allocation on a rolling average. Some suggested that a separate DOI funding prioritization model needs to be tailored to Alaska, rather than following that of the conterminous United States, because of the differences in values and suppression tactics between the two regions. Interviewees consistently mentioned limited funding as an issue for staffing, training, preparedness, fuels, and suppression. As fire extent and severity is expected to increase, this problem will only become exacerbated. Managers either need more money or a review of value prioritization, because increasingly they may not be able to meet all of their protection obligations. Additional exploration of how to improve upon current budgeting strategies is also warranted.
2. <u>Addressing staffing challenges:</u> Interviewees discussed several capacity challenges resulting from lack of staff and lack of expertise among managers. Some of the primary challenges mentioned by interviewees were needing more recruits, needing to hire staff for a period that matches the lengthening fire season, needing easier interagency hiring processes to share staff between agencies, and needing more localized discretion over staffing regulations in order to tailor capacity to expected needs.
3. <u>Protection of remote sites and caribou habitat:</u> Interviewees mentioned that some values generate controversy due to the high cost of protection. These are most often sites under the full or modified protection option that may receive lower priority for protection during large fire years when resources are limited. A few of the more controversial values listed by interviewees include remote uninhabited sites, such as cabins or Native

allotments, and large areas of land, such as caribou winter range. At the same time, interviewees indicated the significant natural resource and subsistence use value of protecting cabins, Native allotments, and caribou habitat. This issue may benefit from some additional dialogue.

4. Climate change adaptation and mitigation: Interviewees discussed the possible need for broad changes in fire management approaches in the future to adapt the system to the challenges posed by climate change, including broader use of the full and critical management option designation to diminish risk and increased use of fuel breaks to facilitate suppression and natural burning under scenarios of increased fire activity. Interviewees also described increasing concern among the fire management community regarding mitigation of greenhouse gas emissions caused by wildland fire. ANCSA Corporations have recently begun asking the agencies to protect some areas of forest as greenhouse gas emissions offset credits. Interviewees mentioned that people within the agencies have begun to discuss the possibility of protecting permafrost as a carbon sink. Despite the benefits of emissions mitigation, interviewees explained that protecting timber and permafrost from fire would require significant risk monitoring efforts to determine which areas must be protected in full at any given time and significant expenditure for remote suppression operations. Considering the expected effects of climate change and the magnitude of Alaska's timber and permafrost carbon sinks, agencies have an opportunity to discuss critical climate change adaptation and mitigation measures in fire management.

Projections of future change

There are several key takeaways, related to the three hypotheses, from the simulation work performed to develop projections of future change. First, key metrics of future fire regimes will be significantly different than those for the historical data. Regardless of the projections of future change and the management scenarios considered, projections of future fire regimes all suggest that the next several decades will see elevated fire activity relative to the historical from 1950-2013. Second, different management scenarios did not result in significant differences in key metrics of fire regimes. We constructed scenarios of future management that would bound what was possible in terms of landscape scale management. Regardless, there was no significant difference among the management scenarios in terms of the future fire regimes. This is due to the overwhelming impact of the changing climate on increasing fire activity. Finally, we did not see that cost estimates were significantly different among future management scenarios.

Key issues and recommendations

The Alaska wildland fire governance system's interagency arrangements favor adaptability and responsiveness to changing circumstances, including current resource limitations, but transformations in fire regimes may cause unsustainable capacity failures that would necessitate changes in fire governance. These could include changes in the values and priorities for management, interagency structure, or internal or external policy. To prepare for possible needed changes, the agencies will benefit from continuing to utilize their adaptive mechanisms, such as regular interagency communications, annual interagency meetings, and collaborative arrangements to review and improve the policies, structure, and management goals that are not working or may not work in the future. The agencies must continually maintain good relationships within the system and with the public and use the best equipment and science available to be able to respond to the challenges of a constantly changing environment. Our specific recommendations for governance include the following:

- Federal and state managers would benefit from a structured decision-making exercise to identify priorities, capacity needs, and consequences of declining resources in Alaska.
- To address specific priorities and capacity needs, the agencies would benefit from higher levels of funding and staffing.
- Improved interagency communication and the sharing of planning responsibilities among agency administrators and fire managers would help integrate land and fire management considerations for more effective management approaches.
- To augment capacity, it would be beneficial to streamline training and certification requirements to support seasonal hiring, interagency resource sharing, and use of the Emergency Firefighting Program.
- Alaska would benefit from community-based capacity building, seed grants, and fuels treatment funding to increase capacity for hazardous fuels reduction.
- A relatively small investment to create a venue or convene a team to address key issues, including protection of Native allotments and other remote sites, would be valuable.

Future Research

Although interviews were in-depth and broad-reaching, additional interviewees may have provided some additional details or nuances. Moreover, broader sampling would be needed to gain a deeper understanding of the perspectives of private citizens, members of Native tribes, and community-based organizations. Another area for ongoing social science research is to understand how existing institutions are repurposed, reshaped, replaced, or sometimes evaded as social-ecological systems evolve and as disturbance becomes increasingly common, and how different emergent institutions may more or less successfully fit within existing contexts.

The results of the simulation experiment address patterns that emerge at the landscape scale. These large-scale patterns are important for framing the likely future of the boreal forest. While the ability for varying fire management to exert an effect on the landscape pattern seems low, this result can help focus efforts. For example, several members of the fire management community have suggested protecting areas of high-value permafrost. The results of this work suggest that efforts such as these will meet with limited success due to the relentless and overwhelming impacts of the climate forcing.

One of the issues that is not addressed by this simulation experiment is the impact of small-scale fuel breaks on the ability to effectively implement point-protection of critical infrastructure. Anecdotal evidence suggests that there can be high utility in the development of fuel breaks around communities. The results of this simulation experiment suggest that the allocation of finite resources towards efforts such as these are more likely to be successful than any attempts to use landscape scale management to combat the climate forcing.

As more data are collected on the ever-changing boreal forest, models like ALFRESCO need to be updated. There is no historical analog for the current and likely-future state of the boreal forest and changes are dynamically occurring with respect to the structure and function of the boreal forest ecosystem. As dynamics change, it is likely that assumptions made in the model that were driven by the analysis of historical data will need to be re-visited and revised.

Literature Cited

Alaska Wildland Fire Coordinating Group (AWFCG). 2017. Alaska interagency wildland fire management plan 2016. AWFCG, Fairbanks, Alaska, USA. [online] URL: https://fire.ak.blm.gov/administration/awfcg.php

Alexander, H. D., and M. C. Mack. 2017. Gap regeneration within mature deciduous forests of Interior Alaska: implications for future forest change. Forest Ecology and Management 396:35-43.https://doi.org/10.1016/j.foreco.2017.04.005

Beverly, J. L. 2017. Time since prior wildfire affects subsequentfire containment in black spruce. International Journal of Wildland Fire 26(11):919-929. https://doi.org/10.1071/WF17051

Braun, V., and V. Clarke. 2006. Using thematic analysis in psychology. Qualitative Research in Psychology 3(2):77-101.https://doi.org/10.1191/1478088706qp063oa

Brunner, R. D., and A. H. Lynch. 2010. Adaptive governance and climate change. American Meteorological Society, Boston,Massachusetts, USA. http://dx.doi.org/10.1007/978-1-935704-01-0

Cary, G. J., I. D. Davies, R. A. Bradstock, R. E. Keane, and M.D. Flannigan. 2017. Importance of fuel treatment for limiting moderate-to-high intensity fire: findings from comparative fire modelling. Landscape Ecology 32(7):1473-1483. https://doi.org/10.1007/s10980-016-0420-8

Chapin, F. S., S. F. Trainor, P. Cochran, H. Huntington, C. Markon, M. McCammon, A. D. McGuire, and M. Serreze. 2014.Alaska. Pages 514-536 in J. M. Melillo, T. C. Richmond, and G.W. Yohe, editors. Climate change impacts in the United States: the third national climate assessment. U.S. Global Change Research Program, Washington, D.C., USA. https://doi.org/10.7930/J00Z7150

Chapin, F. S., S. F. Trainor, O. Huntington, A. L. Lovecraft, E.Zavaleta, D. C. Natcher, A. D. McGuire, J. L. Nelson, L. Ray, M.

Cosens, B. A., R. K. Craig, S. Hirsch, C. A. (T.) Arnold, M. H.Benson, D. A. DeCaro, A. S. Garmestani, H. Gosnell, J. Ruhl, and E. Schlager. 2017. The role of law in adaptive governance. Ecology and Society 22(1):30. https://doi.org/10.5751/ES-08731-220130

Cosens, B., L. Gunderson, C. Allen, and M. H. Benson. 2014. Identifying legal, ecological and governance obstacles, and opportunities for adapting to climate change. Sustainability 6 (4):2338-2356. https://doi.org/10.3390/su6042338

Cosens, B. A., L. Gunderson, and B. C. Chaffin. 2018. Introduction to the Special Feature Practicing Panarchy: Assessing legal flexibility, ecological resilience, and adaptive governance in regional water systems experiencing rapid environmental change. Ecology and Society 23(1):4. https://doi.org/10.5751/ES-09524-230104

Craig, R. K., A. S. Garmestani, C. R. Allen, C. A. Arnold, H. Birge, D. A. DeCaro, A. K. Fremier, H. Gosnell, and E. Schlager. 2017. Balancing stability and flexibility in adaptive governance: an analysis of tools available in U.S. environmental law. Ecology and Society 22(2):3. https://doi.org/10.5751/ES-08983-220203

DeCaro, D., B. C. Chaffin, E. Schlager, A. S. Garmestani, and J. B. Ruhl. 2017. Legal and institutional foundations of adaptive environmental governance. Ecology and Society 22(1):32. https://doi.org/10.5751/ES-09036-220132

Dietz, T., E. Ostrom, and P. C. Stern. 2003. The struggle to govern the commons. Science 302(5652):1907-1912. https://doi.org/10.1126/science.1091015

Duffy, P. A., J. E. Walsh, J. M. Graham, D. H. Mann, and T. S. Rupp. 2005. Impacts of large-scale atmospheric-ocean variability on Alaskan fire season severity. Ecological Applications 15(4):1317-1330. https://doi.org/10.1890/04-0739

Flannigan, M. D., B. M. Wotton, G. A. Marshall, W. J. de Groot, J. Johnston, N. Jurko, and A. S. Cantin. 2016. Fuel moisture sensitivity to temperature and precipitation: climate change implications. Climatic Change 134(1-2):59-71. https://doi. org/10.1007/s10584-015-1521-0

Folke, C., T. Hahn, P. Olsson, and J. Norberg. 2005. Adaptive governance of social-ecological systems. Annual Review of Environment and Resources 30:441-473. https://doi.org/10.1146/annurev.energy.30.050504.144511

Folke, C., L. Pritchard, F. Berkes, J. Colding, and U. Svedin. 2007. The problem of fit between ecosystems and institutions: ten years later. Ecology and Society 12(1):30. https://doi.org/10.5751/ ES-02064-120130

Jandt, R., K. Joly, C. R. Meyers, and C. Racine. 2008. Slow recovery of lichen on burned caribou winter range in Alaska tundra: potential influences of climate warming and other disturbance factors. Arctic, Antarctic, and Alpine Research 40 (1):89-95.

Johnstone, J. F., F. S. Chapin III, T. N. Hollingsworth, M. C. Mack, V. Romanovsky, and M. Turetsky. 2010. Fire, climate change, and forest resilience in interior Alaska. Canadian Journal of Forest Research 40(7):1302-1312. https://doi.org/10.1139/ X10-061

Joly, K., P. A. Duffy, and T. S. Rupp. 2012. Simulating the effects of climate change on fire regimes in Arctic biomes: implications for caribou and moose habitat. Ecosphere 3(5):1-18. https://doi.org/10.1890/ES12-00012.1

Jones, B. M., G. Grosse, C. D. Arp, E. Miller, L. Liu, D. J. Hayes, and C. F. Larsen. 2015. Recent Arctic tundra fire initiates widespread thermokarst development. Scientific Reports 5:15865. https://doi.org/10.1038/srep15865

Kasischke, E. S., and M. R. Turetsky. 2006. Recent changes in the fire regime across the North American boreal region-spatial and temporal patterns of burning across Canada and Alaska. Geophysical Research Letters 33(13):L13703. https://doi. org/10.1029/2006GL026946

Kasischke, E. S., D. L. Verbyla, T. S. Rupp, A. D. McGuire, K. A. Murphy, R. Jandt, J. L. Barnes, E. E. Hoy, P. A. Duffy, M. Calef, and M. R. Turetsky. 2010. Alaska's changing fire regimeimplications for the vulnerability of its boreal forests. Canadian Journal of Forest Research 40(7):1313-1324. https://doi. org/10.1139/X10-098

Kelly, R., M. L. Chipman, P. E. Higuera, I. Stefanova, L. B. Brubaker, and F. S. Hu. 2013. Recent burning of boreal forests exceeds fire regime limits of the past 10,000 years. Proceedings of the National Academy of Sciences of the United States of America 110(32):13055-13060. https://doi.org/10.1073/pnas.1305069110

Knapp, C. N., and S. F. Trainor. 2015. Alaskan stakeholderdefined research needs in the context of climate change. Polar Geography 38(1):42-69. https://doi.org/10.1080/1088937X.2014.999844

Mack, M. C., M. S. Bret-Harte, T. N. Hollingsworth, R. R. Jandt, E. A. G. Schuur, G. R. Shaver, and D. L. Verbyla. 2011. Carbon loss from an unprecedented Arctic tundra wildfire. Nature 475:489-492. https://doi.org/10.1038/nature10283

Mann, D. H., T. S. Rupp, M. A. Olson, and P. A. Duffy. 2012. Is Alaska's boreal forest now crossing a major ecological threshold? Arctic, Antarctic, and Alpine Research 44(3):319-331. http://doi. org/10.1657/1938-4246-44.3.319

Melvin A. M., G. Celis, J. F. Johnstone, A. D. McGuire, H. Genet, E. A. G. Schuur, T. S. Rupp, and M. C. Mack. 2018. Fuelreduction management alters plant composition, carbon and nitrogen pools, and soil thaw in Alaskan boreal forest. Ecological Applications 28(1):149-161. https://doi.org/10.1002/eap.1636

Melvin, A. M., J. Murray, B. Boehlert, J. A. Martinich, L. Rennels, and T. S. Rupp. 2017. Estimating wildfire response costs in Alaska's changing climate. Climatic Change 141(4):783-795. https://doi.org/10.1007/s10584-017-1923-2

Morrison, T. H., W. N. Adger, K. Brown, M. C. Lemos, D. Huitema, and T. P. Hughes. 2017. Mitigation and adaptation in polycentric systems: sources of power in the pursuit of collective goals. Wiley Interdisciplinary Reviews-Climate Change 8(5):e479. https://doi.org/10.1002/wcc.479

Moseley, C., and S. Charnley. 2014. Understanding microprocesses of institutionalization: stewardship contracting and national forest management. Policy Sciences 47(1):69-98. https://doi.org/10.1007/s11077-013-9190-1

North, M., B. M. Collins, and S. Stephens. 2012. Using fire to increase the scale, benefits, and future maintenance of fuels treatments. Journal of Forestry 110(7):392-401. https://doi. org/10.5849/jof.12-021

Olsson, P., C. Folke, and F. Berkes. 2004. Adaptive comanagement for building resilience in social-ecological systems. Environmental Management 34(1):75-90. https://doi.org/10.1007/s00267-003-0101-7

Olsson, P., C. Folke, and T. P. Hughes. 2008. Navigating the transition to ecosystem-based management of the Great Barrier Reef, Australia. Proceedings of the National Academy of Sciences of the United States of America 105(28):9489-9494. https://doi.org/10.1073/pnas.0706905105

Pastick, N. J., P. Duffy, H. Genet, T. S. Rupp, B. K. Wylie, K. D. Johnson, M. T. Jorgenson, N. Bliss, A. D. McGuire, E. E. Jafarov, and J. F. Knight. 2017. Historical and projected trends in landscape drivers affecting carbon dynamics in Alaska. Ecological Applications 27(5):1383-140 2. https://doi.org/10.1002/eap.1538

Rijke, J., R. Brown, C. Zevenbergen, R. Ashley, M. Farrelly, P. Morison, and S. van Herk. 2012. Fit-for-purpose governance: a framework to make adaptive governance operational. Environmental Science and Policy 22:73-84. http://dx.doi. org/10.1016/j.envsci.2012.06.010

Rupp, T. S., P. Duffy, M. Leonawicz, M. Lindgren, A. Breen, T. Kurkowski, A. Floyd, A. Bennett, and L. Krutikov. 2016. Climate simulations, land cover, and wildfire in Alaska. Pages 17-52 in Z. Zhu and A. D. McGuire, editors. Baseline and projected future carbon storage and greenhouse-gas fluxes in ecosystems of Alaska. Professional Paper 1826. U.S. Geological Survey, Reston,

Schultz, C. A., M. P. Thompson, and S. McCaffrey. 2019. Forest Service fire management and the elusiveness of change. Fire Ecology, in press.

Schuur, E. A. G., J. Bockheim, J. G. Canadell, E. Euskirchen, C. B. Field, S. V. Goryachkin, S. Hagemann, P. Kuhry, P. M. Lafleur, H. Lee, G. Mazhitova, F. E. Nelson, A. Rinke, V. E. Romanovsky, N. Shiklomanov, C. Tarnocai, S. Venevsky, J. G. Vogel, and S. A. Zimov. 2008. Vulnerability of permafrost carbon to climate change: implications for the global carbon cycle. BioScience 58 (8):701-714. https://doi.org/10.1641/B580807

Todd, S. K., and H. A. Jewkes. 2006. Wildland fire in Alaska: a history of organized fire suppression and management in the Last Frontier. Bulletin Number 114. University of Alaska Fairbanks, USA. [online] URL: https://www.uaf.edu/files/snre/B114.pdf

Trainor, S. F., M. Calef, D. Natcher, F. S. Chapin III, A. D. McGuire, O. Huntington, P. Duffy, T. S. Rupp, L. DeWilde, M. Kwart, N. Fresco, and A. L. Lovecraft. 2009. Vulnerability and adaptation to climate-related fire impacts in rural and urban interior Alaska. Polar Research 28(1):100-118. https://doi.org/10.1111/j.1751-8369.2009.00101.x

U.S. Department of the Interior, Bureau of Indian Affairs, Bureau of Land Management, Fish and Wildlife Service, National Park Service, U.S. Department of Agriculture, Forest Service, and State of Alaska, Department of Natural Resources (USDOI BIA etal.). 2016. Alaska master cooperative wildland fire management and Stafford Act response agreement. Washington, D.C., USA. [online] URL: https://fire.ak.blm.gov/administration/asma.php

Wotton, B. M., M. D. Flannigan, and G. A. Marshall. 2017. Potential climate change impacts on fire intensity and key wildfire suppression thresholds in Canada. Environmental Research Letters 12(9):095003. https://doi.org/10.1088/1748-9326/aa7e6e

Wyborn, C., and R. P. Bixler. 2013. Collaboration and nested environmental governance: scale dependency, scale framing, and cross-scale interactions in collaborative conservation. Journal of Environmental Management 123:58-67. https://doi.org/10.1016/j.jenvman.2013.03.014

Yin, R. K. 2016. Qualitative research from start to finish. Second edition. Guilford, New York, New York, USA.

Young, A. M., P. E. Higuera, P. A. Duffy, and F. S. Hu. 2017. Climatic thresholds shape northern high-latitude fire regimes and imply vulnerability to future climate change. Ecography 40 (5):606-617. https://doi.org/10.1111/ecog.02205

Appendix A: Contact Information for Key Project Personnel

Courtney Schultz, Ph.D.
Associate Professor of Forest & Natural Resource Policy
Director of the Public Lands Policy Group at CSU
Department of Forest and Rangeland Stewardship
Colorado State University
Office phone: 970-491-6556
courtney.schultz@colostate.edu
https://sites.warnercnr.colostate.edu/courtneyschultz/

Paul Duffy, Ph.D.
Vice President
Neptune and Company, Inc.
office: (970) 416-6488
cell: (970) 420-7199
http://www.neptuneandco.com

Nancy Fresco, Ph.D.
Network Coordinator, SNAP & Associate Director, CIFAR
International Arctic Research Center (IARC) 415A#1,
University of Alaska Fairbanks
Fairbanks AK 99709
nlfresco@alaska.edu
(907)474-2405

Randi Jandt
Fire Ecologist
Akasofu Building (IARC), 2158 Koyukuk Drive
University of Alaska, Fairbanks
Fairbanks, AK 99775
(907) 474-5088
rjandt@alaska.edu

Appendix B: List of Completed/Planned Scientific/Technical Publications/Science Delivery Products

Articles in peer-reviewed journals

Rutherford, T. K., and C. A. Schultz. 2019. Adapting wildland fire governance to climate change in Alaska. Ecology and Society 24 (1):27. https://doi.org/10.5751/ES-10810-240127

Duffy, P., C. A. Schultz, and Rutherford, T. K. Fire management and climate change in the Alaskan boreal forest: Implications for future structure and function. (in review) Frontiers in Ecology and the Environment.

Technical reports

Rutherford, T. K., and C. A. Schultz. 2017. Challenges and Opportunities in Alaska Fire Management: Adapting to Climate Change A Practitioner's Report on Interview Findings. Colorado State University Public Lands Policy Group. Available at: https://sites.warnercnr.colostate.edu/courtneyschultz/wp-content/uploads/sites/23/2017/10/Alaska-Fire-Management-and-Climate-Change.pdf

Policy Briefing Paper

Schultz, Courtney, Paul Duffy, Tait Rutherford, Nancy Fresco, and Randi Jandt. 2018. Adapting Wildfire Management to Climate Change in Alaska. Colorado State University Public Lands Policy Group. Briefing paper #3. Available at: https://sites.warnercnr.colostate.edu/courtneyschultz/wp-content/uploads/sites/23/2018/04/PolicyBrief_final.pdf

Graduate thesis

Rutherford, Tait Kater 2018. Climate Change Adaptation in Wildland Fire Management and Governance in Alaska. Department of Forest and Rangeland Stewardship. In partial fulfillment of the requirements for the Degree of Master of Science. Colorado State University, Fort Collins, Colorado. Available at: https://mountainscholar.org/handle/10217/191459

Websites

https://www.snap.uaf.edu/tools/wildfire-management-projections

Webinars

February 1, 2017: Webinar – "New Tool for Future Scenario Building for Alaska Fire Managers" hosted by the Alaska Fire Science Consortium; Available at: https://www.frames.gov/event/426683

Conference Abstracts

May 23, 2018. Rutherford, T.K., C.A. Schultz. "The Future of Fire Management in Alaska: Adapting Approaches in Light of Current and Predicted Effects due to Climate Change." Fire Continuum Conference, Missoula, MT. Oral Presentation in Organized Session.

Abstract: Climate change is causing an increase in wildland fire activity in the boreal and tundra ecosystems of Alaska, threatening the capacity of federal and state fire management agencies to meet management goals. Our research involved an iterative process of fire and vegetation modeling, science delivery, and direct communication with fire managers to explore how fire management agencies will respond to the pressures of climate change. We evaluated how fire regimes will change under current management approaches using projections created in the Alaska Frame-Based Ecosystem Code (ALFRESCO) model. Through interviews with fire managers and stakeholders, we then sought perceptions of current and projected challenges, particularly regarding climate change, and possible needed changes to adapt to those challenges. We then modified the ALFRESCO model using possible changes to management approaches that we developed based on our interviews and used these updated projections in a second round of communication with managers to understand possible future strategies and needs. We discuss our findings, focusing on the aspects of the fire management system that both support and impede managers' ability to adapt to changing conditions. While we found that budgeting and staffing challenges are especially salient issues for the agencies, managers also emphasize the importance of adapting fire management by increasing and better prioritizing the use of suppression tactics and fuels management strategies to mitigate risk to communities and valued sites. This will require continued utilization of the unique interagency strategies in place in Alaska but also may necessitate some fundamental changes in management priorities, policy, and approaches.

November 17, 2017. Rutherford, T.K., Schultz, C.A. "Preparing for Future Fire: Governance Change in the Alaska Wildland Fire Management System," Society of American Foresters National Convention, Albuquerque, NM.

Abstract: Climate change is causing an increase in the severity and frequency of wildland fire in the boreal and tundra regions of Alaska. Federal and state fire managers in Alaska face an increasing demand for fire suppression as the wildland urban interface expands. Yet in a complex mosaic of land jurisdiction and interagency coordination, resources for suppression have not risen to meet this demand. Considering these challenges, managers are looking for projections of future fire regimes to reduce uncertainty and prepare managers for future decision making. In this graduate thesis research project funded by the Joint Fire Science Program (JFSP), I am studying how fire management agencies will respond to the pressures of climate change. The project is based on manager reactions to a new online fire regime projection tool created in a parallel project using the Alaska Frame-Based Ecosystem Code (ALFRESCO) model. Through interviews with fire managers and stakeholders, I am looking for perceptions of future management options and pathways to achieve changes in governance arrangements and fire management policy. Data gathered in these interviews will help to create future management scenarios for presentation back to managers. I apply theories of policy and social learning to manager narratives to understand the process of fire governance change in Alaska. Improved understanding of needed changes in the governance system and future management scenarios can help decision makers prepare for the challenges of climate change.

Appendix C: Metadata

1. For our human subjects' data, we have uploaded a word document with our final codes. This data is not reasonably deidentifiable and therefor is not archived. The only change from our data management plan was that our coding took plan in a program called Dedoose, rather than in nVivo. All of our long-term data management structures and procedures are in place.
2. For the ALFRESCO modeling component, we will upload the complete metadata. The following is an abstract for the metadata that will be submitted.

   This set of files include annual model outputs from ALFRESCO (ALaska FRame-based EcoSystem COde), a landscape scale fire and vegetation dynamics model. These specific outputs are the result of a Joint Fire Science Program (JFSP) project, and consist of three comparative sets of runs to explore potential management treatment options. This includes historical Fire Management Options (FMOs) https://fire.ak.blm.gov/content/maps/aicc/Large%20Maps/Alaska_Fire_Management_Options.pdf as well as potential modifications to those options into the future, with fire spread sensitivity altered to reflect changes. Current suppression levels exist as Critical, Full, Modified, and Limited, in order of highest to lowest levels of suppression efforts. Treatment options for the purposes of this study are labeled below as TX0, TX1, and TX2.

   TX0—Baseline: Current fire management options are continued into the future, as this scenario assumes no change to current management practices.

   TX1—More Full Suppression: Current Full suppression areas were extended by a 10km buffer and were applied to future simulations. This represents an overall increase in suppression efforts in the affected areas.

   TX2—No Full Suppression: Full and Modified suppression areas were re-assigned to Limited status for the purpose of future simulations. Critical areas remained unchanged. This represents an overall decrease in suppression efforts.

   Climate models and emission scenarios:
   For all GCMs, RCPs 4.5, 6.0, and 8.5 were simulated.
   The following GCMs from CMIP5 were run as part of this study:
   - IPSL-CM5A-LR
   - GFDL-CM3
   - GISS-E2-R
   - MRI-CGCM3
   - NCAR-CCSM4

   Variables include:

Veg: The dominant vegetation for this cell. Current values are:
0 = Not Modeled
1 = Tundra (otherwise not listed)
2 = Black Spruce
3 = White Spruce
4 = Deciduous Forest
5 = Shrub Tundra
6 = Graminoid Tundra
7 = Wetland Tundra
8 = Barren / Lichen / Moss
9 = Temperate Rainforest

Age: This the age of the vegetation in each cell. An Age value of 0 means it transitioned in the previous year.

Basal Area: The accumulation of basal area of white spruce in tundra cell, and is influenced by seed dispersal, growth of biomass, climate data, and other factors.
units = m^2/ ha

Burn Severity: This is a categorical burn severity level of the previous burn in the current cell, influenced by fire size and slope. For example, a burn severity value in a file with year 1971 in the file name means that the severity level given to that file occurred in the fire that occurred in year 1970.
   0=No Burn
   1=Low
   2=Moderate
   3=High w Low Surface Severity
   4=High w/ High Surface Severity

Fire Scar: These are the unique fire scars. Each cell has three values.
   Band 1 - Year of burn
   Band 2 - Unique ID for the simulated fire for that simulation year
   Band 3 - Whether or not the cell was an ignition location for a fire. There will only be 1 ignition cell per fire per year.
      0 = not ignition
      1 = ignition point

Appendix D: Questionnaire, Interview, and Workshop Materials

On-line Questionnaire Items

1. What is your current position and what is your role in Alaska fire management?
2. What current challenges are you and the broader fire management community facing in Alaska fire management? We are interested in capacity, policy, jurisdictional, financial, or ecological challenges, among other challenges we might not have considered. If there are too many to mention, consider listing your top three or four.
3. To what extent have you explored the ALFRESCO website? How much have you used it, and for what purposes?
4. What new information do the ALFRESCO fire regime projections give you, if anything?
5. Are there other ways you'd like to see the information packaged or presented (e.g. time frames, jurisdictional scale, etc.)?
6. Does seeing these model outputs change your perspective on future fire management approaches and needs? In other words, does this information make you think about the problem in new way?
7. Is there anything else you would like to tell us at this time?

Interview Guide

1. What is your current position and involvement in Alaska fire management?
2. Understanding of current management
   - What are the current priorities for fire management Alaska? For your organization specifically?
   - What are current management approaches that you (or your organization) use in your job (to meet your agency's priorities)? In what ways are current approaches effective? Not effective?
   - What are the primary challenges faced today in AK fire management?
   - How have you seen costs and resource needs change in recent years? What has driven these changes?
3. Understanding future management options
   - How do you think management approaches (for example, the ones you mentioned) will need to change in the future?
   - Do you anticipate changes to funding or other resource needs in the future?
   - We will be modeling the effects for fire and vegetation for different future management scenarios and would like to know what scenarios you think we should consider. We shared with you a possible future fire management scenario. Can you tell us what you think of it? Are there others you think we should consider?
   - What would be necessary to make these management approaches possible?
   - What do you think are some barriers to achieving the necessary changes?
4. Policy pathways
   - Do you see any challenges in the current interagency cooperative system for fire suppression? (Cue to discuss billing/cost-sharing system if they do not mention)
   - Do current policies support fire management goals?

- Do you have any recommendations for changing interagency policy or planning (the things you mentioned *or* jurisdictional boundaries, cost sharing, or land management goals)?
- Are there changes in policy or management goals your agency might need to undertake?

5. Science delivery
    - Have you looked at the new fire regime projections tool on the SNAP website?
    - Have the projections been useful or given you new information?
    - Is the website useful (intuitive, understandable)?
    - What do you think are the primary science needs of managers? What science would they like to see?
6. Closing
    - Is there anything else you'd like to discuss or that I should have asked about?
    - Whom else should I be talking to?
    - Would you be willing to take a follow up call from us if we have further specific questions when we are building management scenarios into the models?

Workshop Invitation

Project Overview

These workshops are part of a Joint Fire Science Program project "*Impacts of Climate and Management Options on Wildland Firefighting in Alaska: Implications for Operational Costs and Complexity under Future Scenarios*." Courtney Schultz (courtney.schultz@colostate.edu) is the PI, working with her graduate student Tait Rutherford, co-PIs Paul Duffy (Neptune, Inc.), Nancy Fresco (UAF), and collaborator Randi Jandt (AFSC). The goal of the project is to explore how Alaska fire management will respond to changes in fire regimes under different climate change projections. In the first two phases of the project, we did the following: 1) Used the ALFRESCO model to develop fire regime projections, and 2) Interviewed 41 fire managers to explore current and future priorities, challenges, and management approaches. We presented our findings to date at the 2017 Fall Fire Review. In this upcoming phase of the project, we are inviting you to join us for workshops we are hosting in March 2018.

Workshops Summary

When and where: March 7th, 2018, in Fairbanks; March 8th, 2018, in Anchorage

Objective: Explore the following questions, based on fire regime projections and historical suppression cost data:

1. How might current and future management approaches affect fire management priorities or valued resources?
2. What are anticipated future resource needs and capacity limitations?
3. Will policies or other aspects of agency practice need attention in order to accommodate anticipated challenges?

What to expect: Workshops will last about 6 hours, with a break for lunch. We will present model outputs based on different management approaches and information on anticipated costs and impacts. The majority of our time will be spent in group discussion. We expect 5-20 participants at each workshop. We will take notes on discussions to support analyses for publication and to develop presentations to policymakers. We will maintain confidentiality of individual contributions in anything we publish or distribute.

To prepare: You may want to familiarize yourself with our online fire regime projections tool and the webinar that introduces it, and our report on interview results. These are available at the following links:

Online model: https://uasnap.shinyapps.io/jfsp-v10/

Webinar: https://www.frames.gov/partner-sites/afsc/events/previous-events/previous-webinars/duffy-schultz-feb-2017/

Interview report: https://sites.warnercnr.colostate.edu/courtneyschultz/wp-content/uploads/sites/23/2017/10/Alaska-Fire-Management-and-Climate-Change.pdf

To participate: If you would like to participate in one of the workshops, please contact Nancy Fresco at nlfresco@alaska.edu.

Model Outputs and Management Alternatives

The ALFRESCO model simulates fire activity under different climate projections and the output can be processed to generate estimates of fire and vegetation characteristics for the tundra and boreal regions of Alaska for the years 1950 to 2099, including:

Fire Vegetation (3 boreal forest and 4 tundra cover types)

· Annual area burned · Cover area
· Annual fire count · Stand age
· Annual average fire size

ALFRESCO uses General Circulation Models (GCMs) and Representative Concentration Pathways (RCPs) developed as part of the Intergovernmental Panel on Climate Change (IPCC) AR5 to develop projections of future fire activity that can be used to explore the implications of future climate on fire and vegetation trends. We are working to connect this information to past cost information to better understand the implications of model outputs in terms of future costs and resource needs.

We will explore the implications of climate change for future fire and vegetation in Alaska based on historical fire data. Drawing from managers' suggestions in interviews, we also have developed two "management alternatives" to modify the business-as-usual projections. We will use these two alternatives to explore some potentially different approaches to management and their implications. In the first alternative, we expand critical and full management option buffers around communities to determine whether this can effectively slow the threat of fire to communities; we also explore the associated implications for fuel loading and changes in the dominant vegetation on the landscape. In the second alternative, we explore a variation on this by including prescribed fire in the initial attack buffers. Our intent is to use these different approaches and model results to assess the costs and benefits of possible changes to initial attack planning and fuels management.

Workshop Agenda

Workshop Objectives

This workshop is part of a Joint Fire Science Program project entitled "*Impacts of Climate and Management Options on Wildland Firefighting in Alaska: Implications for Operational Costs and Complexity under Future Scenarios*." The goal of the project is to explore how Alaska fire management will respond to changes in fire regimes under climate change projections. We will explore the following questions, based on fire regime projections and historical suppression cost data:

1. How might current and future management approaches affect fire management priorities or valued resources?
2. What are anticipated future resource needs and capacity limitations?
3. Will policies or other aspects of agency practice need attention to accommodate anticipated challenges?

Based on answers to these questions, we hope to develop content for policy briefs that we can deliver to policymakers on behalf of the Alaska fire management community.

Agenda: Wednesday, March 7, Fairbanks

8:15-8:30am	Introductions
8:30-8:50am	Overview of project (PowerPoint presentation)
8:50-9:20am	Overview of model and business-as-usual model results (PowerPoint presentation); questions
9:20-9:30am	Short break
9:30-10:30am	Breakout groups to discuss model implications for priorities, planning, resource limitations, and policy needs
10:30-10:40am	Break
10:40-11:30am	Reconvene as large-group and discuss results of breakout group conversations
11:30-12:45pm	Lunch
12:45-1:15pm	Overview additional modeling results (PowerPoint presentation); questions
1:15-1:45pm	Large-group discussion of expanded buffer alternative and other planning alternatives
1:45-2:45pm	Large-group discussion of policy priorities, policy delivery strategies, and next steps; closing

Project Team

Courtney Schultz (PI) – Colorado State University	courtney.schultz@colostate.edu; 970-491-6556
Paul Duffy – Neptune, Inc.	paul.duffy@neptuneinc.org; 970-416-6488
Nancy Fresco – University of Alaska Fairbanks	nlfresco@alaska.edu; 907-474-2405
Randi Jandt – Alaska Fire Science Consortium	rjandt@alaska.edu; 907-474-5088
Tait Rutherford – Colorado State University	tait.rutherford@colostate.edu; 970-568-6538